A climatology of particulate pollution in Christchurch

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Abstract

The research presented in this thesis provides a quantitative analysis of atmospheric influences on particulate matter pollution in Christchurch across a wide range of spatial and temporal scales. A complex interaction of low level flow characteristics that form in response to local and regional features of complex terrain, together with an urban setting that is characterised by low density housing, mostly comprised of single storey dwellings that are poorly insulated, regularly leads to nocturnal smog events during winter in Christchurch. Provided synoptic flow is weak, the above mentioned flow interaction promotes flow stagnation over the city, when nocturnal katabatic drainage flows and day-time north-easterly on-shore winds converge over the city. Additionally, undercutting of the density currents promotes highly stable atmospheric stratification close to the surface, so that, in combination, both horizontal and vertical air movement is suppressed. As particulate emission release from solid fuel burning for home heating coincides with this poor atmospheric dispersion potential, particle concentrations can increase substantially so that national air quality guidelines are regularly exceeded during winter in Christchurch.

At the core of this thesis is a classification based approach that examines the day-to-day probabilities of breaches of the national air quality guideline for PM over the last decade at a single location in Christchurch as a result of variations in meteorological conditions alone. It is shown that, based on variations in temperature and wind speed, up to 85% of exceedence occurrence can be explained. From this, concentration trends over time, when meteorological variability is kept to a minimum, are assessed and evidence is found that recent regulatory measures to enhance air quality are beginning to

show positive effects. Atmospheric processes that control pollution dispersion on the mesoscale are investigated through means of atmospheric numerical modelling in a novel approach that assimilates observational climatic wind field averages to drive low level flow for two idealised case studies. It is shown that this approach is able to reproduce the observed diurnal concentration patterns very well and that much of these patterns can be attributed to mesoscale circulation characteristics and associated atmospheric dispersion potential, namely flow stagnation and recirculation of contaminants. When timing of stagnation and subsequent recirculation is such that it occurs within a few hours after peak emission release, concentration increase is enhanced and dilution is delayed, thus severely exacerbating the problem. Links between exceedence probabilities and synoptic situations that favour the degradation of air quality are established and various synoptic transition scenarios are examined with regard to local air quality. The progression of anticyclones across the country is identified to be the dominant synoptic control mechanism and it is shown that latitudinal variation in the progression path determines the extent of expected exceedence probability. On interdecadal hemispheric scales, it is found that a particular combination of local and synoptic atmospheric conditions that favours air quality degradation, shows a re-occurring pattern of frequency maxima (and minima) with a periodicity of approximately 14 - 16 years. For the synoptic part of this interdecadal variability, a close relationship to Southern Hemispheric pressure anomalies in high latitudes is revealed. Finally, for verification of the combined findings and to assess their prediction capability, a validation case study is given which shows that the applied methodology is able to capture day-to-day variations in pollution levels with acceptable (statistically significant) accuracy.

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Dr. Jason M. Tylianakis from Biological Sciences and **Dr. Jennifer Brown** from Mathematics and Statistics also need to be mentioned for introducing me to the wonderful world of statistical computing with R. Their help provided a major milestone regarding the statistical analysis applied in this thesis.

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Environment Canterbury have put great efforts into providing quality assured air quality data on numerous occasions throughout the course of this research for which I am very grateful. In particular, **Teresa Aberkane** has been extremely helpful by quickly responding to data requests and, more importantly, has repeatedly and patiently answered all questioned regarding data collection and quality assurance, amongst other things.

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Chapter 1

Introduction

1.1 Background

The city of Christchurch, located on the east coast of New Zealand's South Island, has an air pollution problem that has long been recognised (e.g. Gray 1889, Pullen 1970, APAC 1959). By far the pollutant of most concern in present day Christchurch is suspended particulate matter with an aerodynamic diameter less than ten micrometers (PM_{10}). Aberkane et al. (2005) reported that it has been shown that during winter 90% of all particles measured as PM_{10} are made up of particles smaller that 2.5 microns ($PM_{2.5}$). However, due to the fact that national legislation focusses on PM_{10}, specific monitoring of $PM_{2.5}$ has only been carried out sporadically over the last decade, with most years showing less that 50% valid data. Since 2004 no monitoring of $PM_{2.5}$ has been reported (Aberkane et al. 2005). Aside from PM_{10}, carbon monoxide (CO) is still of some concern, and in the past, sulphur dioxide (SO_2), released mainly through the burning of coal, contributed to Christchurch's air pollution problem. Nitrous oxides (NO_x) and Ozone (O_3) are of minor importance, mostly due to Christchurch's low population and infrastructural density. Poorly insulated dwellings, together with traditional home heating practices such as coal and wood burning, lead to increased release of particulate matter into the urban atmosphere, especially during winter months. In combination with a complex interaction of low level air masses, which regularly creates highly stagnant and stable atmospheric conditions close to the ground, these particulates can accumulate to high concentrations and lead to reduced air quality in the city. Associated health problems for the urban population are common (Wilton 2001) and hospital admissions are increased during the cold season (McGowan et al. 2002, Hales et al. 2000).

Even though individual management campaigns in relation to air pollution started in the 1930s (Wilton & Ayrey 2002), a structured approach to continuous air quality monitoring in Christchurch has only been implemented since the late 1980s. Moreover, quality assured, reliable air quality data are only available from the late 1990s (Teresa Aberkane, pers. comm.). Therefore, only recently have data sets accumulated to an extent that enables assessment of trend detection in a statistically robust manner. Environment Canterbury (ECan), the local environmental authority, is responsible for ensuring, that National Environmental Standards (NES), established within the framework of the Resource Management Act since 1991, be met in the Canterbury region, including Christchurch. According to the Ministry for the Environment (MfE), the NES requires that the Christchurch urban airshed observes no more than one exceedence of 50 $\mu g/m^3$ for PM_{10} (averaged over the 24 hr period between midnight and midnight) per year by 2013 (MfE 2004). If this is breached, penalties will be imposed, such as restrictions on the granting of resource consents for discharges into air. Various measures to reduce emissions have been implemented by ECan in recent years. These include banning of open fires, and interest-free loans and subsidies for clean heating, among others. Between 1999 - 2006 the NES was exceeded on approximately 30 days each year. To put this in context, one needs to realise that these exceedences mainly happen during the 123 day period between May and August. As a result of this, concerns within ECan are growing as to whether (a) the target of one exceedence per year by 2013 is likely to be reached, (b) the impact of policy measures taken in recent years can already be detected in the concentration time series, and (c) whether additional, possibly more drastic measures need to be taken to meet the target. Therefore, trend assessment of PM_{10} concentrations is of great interest to ECan.

As PM_{10} concentrations are a result of both emission strength and atmospheric dispersion potential, it is necessary that any analysis of trend detection is addressing the issue of identifying and minimising meteorological influences on concentration variation. Pullen (1969) provided a trend assessment of smoke levels in Christchurch with regard to inner-urban variations and concluded that between 1960 - 1969, smoke concentrations had decreased by approximately 30% in the central city, whereas they had increased by this number in the suburban residential areas around the inner city. In his report, however, no attempt was made to account for possible meteorological influences. A few decades later, in a report prepared for ECan, Marsh & Wilkins (2004) provided a first assessment of PM_{10} concentration variation over time in Christchurch when meteorological influence on the concentration time series is accounted for, and concluded that a downward trend is apparent. From the monitoring record, they extracted so-called 'qualifying evenings' (1800 hrs - 2400 hrs) with regard to maximum ground temperature, maximum wind speed and maximum of ground temperature minus temperature at 10 m above ground to reduce meteorological variability. After a further normalisation of these evenings with regard to wind speed and ground temperature, they evaluated trends in central tendencies (mean and median PM_{10} concentrations) over time for numerous different threshold combinations of the meteorological parameters. Even though utilising quantitative statistics, their definition of the thresholds was rather subjective and lacked statistical justification. Appelhans et al. (2007) provided a comprehensive assessment of different approaches to trend analysis for the Christchurch PM_{10} pollution problem and found that all of these basically paint the same picture of a downward trend. The authors contribution to this report is part of this thesis in a slightly revised version (Section 3.3). Scarrott et al. (2009) provided a further suite of statistical approaches to tackle the problem and their conclusions were in line with those of the earlier reports.

With regard to the mentioned meteorological influences on particulate pollution, it is desirable to identify local atmospheric conditions that are associated with varying levels of pollutant concentrations in a general (process oriented) as well as a quantitative manner. Analysis of atmospheric influences from a general perspective provides insight into fundamental processes that contribute to the observed meteorological variability and the associated variations in pollution concentrations, and aids the general understanding of control mechanisms. This is usually achieved through case studies such as the Christchurch Air Pollution Study in 2000 (CAPS 2000; e.g. Kossmann & Sturman 2004), which will be introduced in more detail in Chapter 2. Such fundamental research forms the indispensable basis for any assessment relating to the matter. In order to understand the physical nature of such control mechanisms, all scales in both space and time need to be considered. As discussed in Lovejoy et al. (2009) and Paradisi et al. (2009), atmospheric processes are closely linked in the spatial and temporal domain. Therefore, local to regional processes operating on daily time scales can be expected to be tightly linked to processes at much larger, synoptic to hemispheric scales that operate on seasonal to interdecadal time scales. Local processes that are of importance for the Christchurch air pollution problem have been investigated in some depth already (e.g. APAC 1959, Pullen 1970, Kossmann & Sturman 2004, McKendry et al. 2004, Corsmeier et al. 2006). There is, however, evident lack of the analysis of synoptic or climatological influences on air quality in the city. Internationally, there is a long history of studies that have investigated general synoptic controls on air quality, e.g. Sanchez et al. (1990), Yap & Chung (1977), Heidorn & Yap (1986), McGregor & Bamzelis (1995), O'Hare & Wilby (1995) and more recently Makra et al. (2009), Kuo et al. (2008), Cheng et al. (2007), among others. For New Zealand, however, investigation of synoptic forcing with respect to air quality meteorology is sparse. Khan et al. (2007) have studied relationships between synoptic weather situations and night-time O_3 and NO_x concentrations in Auckland. Also focussed on Auckland, Jiang et al. (2005) have related synoptic weather types and winter time NO_x concentrations during morning rush hour traffic. Owens & Tapper (1977) provided a brief quantitative statistical investigation into both local and synoptic influences on air quality in Christchurch. Apart form this, however, no further examination of meteorological relationships with local air quality on coarser spatial and temporal scales has been reported for Christchurch.

Statistical approaches to identify variations in observed measurements, are mostly quantitative extensions of the fundamental investigation. Yet, they are an essential progression in order to provide a basis for investigations, such as the above mentioned trend assessments, that need a quantitative reference. Furthermore, quantitative assessments of environmental issues are usually of greater value to stakeholders with regard to applicability of the results.

1.2 Objectives of this thesis

As outlined above, efforts have been made to gain a better understanding of the Christchurch air pollution problem, such as investigation of local scale atmospheric processes that lead to degraded air quality. However, the previous section has also highlighted that knowledge gaps are still apparent, especially with regard to quantitative analysis of mechanisms that operate on larger spatial and temporal scales. Therefore, this research is addressing the following main research aims:

I. **Investigation of the nature of trends in particulate pollution in Christchurch on annual to decadal scales.**
Given that only recently sufficiently large data sets of air quality measurements have become available, trend detection of air quality in Christchurch is still rudimentary and will be extended within this thesis through various approaches. For the first time, an approach is implemented that tries to identify historical air quality variation over five decades through utilisation of atmospheric proxies.

II. **Quantification of pollution potential for varying local atmospheric conditions in a Southern Hemispheric mid-latitude setting.**
Pollution potential is investigated on the basis of meteorological observations, so that clear quantitative links between various atmospheric conditions and related pollution probabilities can be established. Focus is on identification of general relationships rather than extreme events.

III. **Identification of regional, synoptic and climatological mechanisms that control particulate pollution potential in an environment dominated by smoke from domestic fires.**

Atmospheric processes that govern air quality in Christchurch are analysed across a range of spatial and temporal scales, so that the local air pollution problem can be put into a wider perspective. Emphasis is again on general processes and the identification of mechanisms and their internal links, but potential external forcings are discussed where appropriate. On the regional scale, a novel numerical modelling approach is implemented that assimilates long-term wind climatologies, so that effects of dominant surface flow modes on local air quality can be investigated.

1.3 Thesis outline

This thesis is clearly located in the field of applied climatology. It is intended that many of the results produced through this research are of immediate value for stakeholders, such as local policy makers. Therefore, careful consideration has been given to applicability and potential reproducibility of the approaches taken here. All statistical analyses have been carried out using R, an open-source software environment for statistical programming and graphics (R Development Core Team 2009). Most graphs in this thesis have been created using the R add-on packages 'lattice' (Sarkar 2010) and 'latticeExtra' (Sarkar & Andrews 2010). Using a command-line based software environment provides the potential of automation of analyses for future repetition. Three main texts were consulted to provide the statistical background for the procedures presented in this study (Hair et al. 2006, Crawley 2005, Storch & Zwiers 1999).

A brief summary of the structure of this thesis is given below. This is followed by a short paragraph that defines some of the terminology that will be repeatedly used throughout this thesis, before a quick overview of the main data used in this thesis is given.

Chapter Two expands the background of the thesis topic that was briefly outlined in Section 1.1, by giving a general overview of the Christchurch air pollution problem in relation to important influencing factors such as topographical setting and general climatology.

Chapter Three provides a quantification of expected exceedence probabilities under varying atmospheric conditions and investigates this pollution potential with regard to influencing local meteorology. Afterwards, a comprehensive assessment of variations in PM_{10} concentrations and associated trends over the last decade is given using two different statistical approaches. This is the chapter that is probably of most interest from a regulatory point of view.

Chapter Four focusses on the general climatology of high pollution events and the investigation of fundamental processes that govern pollution dispersal on local to regional scales in addition to those already identified. A novel approach to numerical atmospheric modelling is introduced in this chapter that uses the numerical simulation environment in an idealised climatological way.

Chapter Five provides an assessment of synoptic controls on air quality in Christchurch and furthermore examines variations in historical pollution potential through the use of meteorological proxies that were identified through the synoptic analysis and through the analysis of local meteorological influences in Chapter 3.

This is followed by **Chapter Six** which provides a brief verification case study to evaluate the findings of the previous chapters, before **Chapter Seven** concludes this thesis by providing a summary of the main findings and discussing the general and future implications of the presented research.

Note, this thesis has a clear atmospheric science perspective and will therefore only briefly discuss issues surrounding air pollution related topics, such as emissions, exposure and general health implications, where appropriate. No specific introduction to these topics is provided. Furthermore, the focus of the meteorological investigations presented here lies in the identification of climatological influences on particulate pollution and therefore, no efforts are made to investigate potential transformations of pollutants in the atmosphere, as such processes generally happen on smaller time scales than the ones considered here.

In the context of this thesis, some general terminology will be used in a somewhat tighter sense than usually common. To avoid ambiguity and confusion, it is necessary to define a few terms that will be repeatedly used throughout this research as defined here, unless explicitly stated otherwise. Throughout this thesis, the terms **'winter'** and **'winter months'** exclusively refer to the 123 day period between May - August. Furthermore, the terms **'pollution'**, **'air quality'**, **'emissions'** and **'concentrations'** will be used throughout this thesis exclusively in reference to particulate matter with an aerodynamic diameter of less than 10 micrometers (PM_{10}). Also, the term **'exceedence'** refers exclusively to the breaching of the NES for PM_{10} (i.e. concentrations > 50 µg/m^3 - averaged over the 24 hours between midnight and midnight).

The climatological data used in this thesis were supplied by the National Institute of Water & Atmospheric Research (NIWA) via their online data base "CliFlo: NIWA's National Climate Database on the Web" (CliFlo - see list of references for details). In July 1994, an automated weather station (AWS) started operation at Christchurch airport and replaced data collection via manual recording charts (Elaine Fouhy, pers. comm.). This has several implications for the analyses implemented in this research. See Section 5.2.1 and Appendix B for further detailed discussions on this.

Air quality data were supplied by ECan. These recordings were made at the NES reference site for Christchurch which is located in the suburb of St. Albans at Coles Place. Other PM_{10} monitoring sites throughout the city exist, however, none of these provides a long enough record for robust climatological analysis as is the focus of this study. As instrumentation changed from a Tapered Element Oscillating Microbalance sampler with the inlet temperature set at 40°C (TEOM) to a Filter Dynamics Measurement System set at 30°C (FDMS) in 2004, a TEOM-FDMS equivalent dataset was created by Environment Canterbury to ensure a continuous record with the highest possible comparability between the two measurement techniques. Environment Canterbury adjusted the recordings obtained from the two instruments using simple linear regression, as part of their quality control process. Although this procedure was undertaken prior to the data being provided to the author, it is important to be aware that some pre-processing has taken place. For an in-depth description of the calibration technique refer to Scarrott et al. (2009). The air quality site at Coles Place also records some meteorological parameters (ambient air temperature at 1 and 10 m above ground, wind speed and direction at 10 m above ground, relative humidity) which were also used for selected analyses in this study.

Chapter 2

The Christchurch air pollution problem

This chapter provides a general geography of Christchurch, by introducing the topography and the general climate of the place, which are important contributing factors to the local air pollution problem.

According to Statistics New Zealand 2006 Census Data, approximately 350,000 people reside within the Christchurch urban area (CCC 2007). As outlined in Section 1.1, the pollutant of main interest in Christchurch is PM_{10}. Over the last decade, ECan has carried out several emission inventories of the city and has identified three major sources of PM_{10} emissions, with varying contributions. Approximately 80% of all emissions stem from emissions released through solid fuel burning for residential heating. The residual 20% are more or less equally divided amongst emissions from traffic and industrial emissions (e.g. Scott & Gunatilaka 2004). Although, it is to be expected that in a coastal city like Christchurch, other natural sources such as wind blown dust, and above all sea salt regularly contribute to pollution levels. However, information on background levels of particulates and contributions of natural sources is not available. The general diurnal pattern of PM_{10} concentrations is shown in Figure 2.1 (an estimation of average diurnal emission release is provided later on in Figure 4.10 - lower panel - in

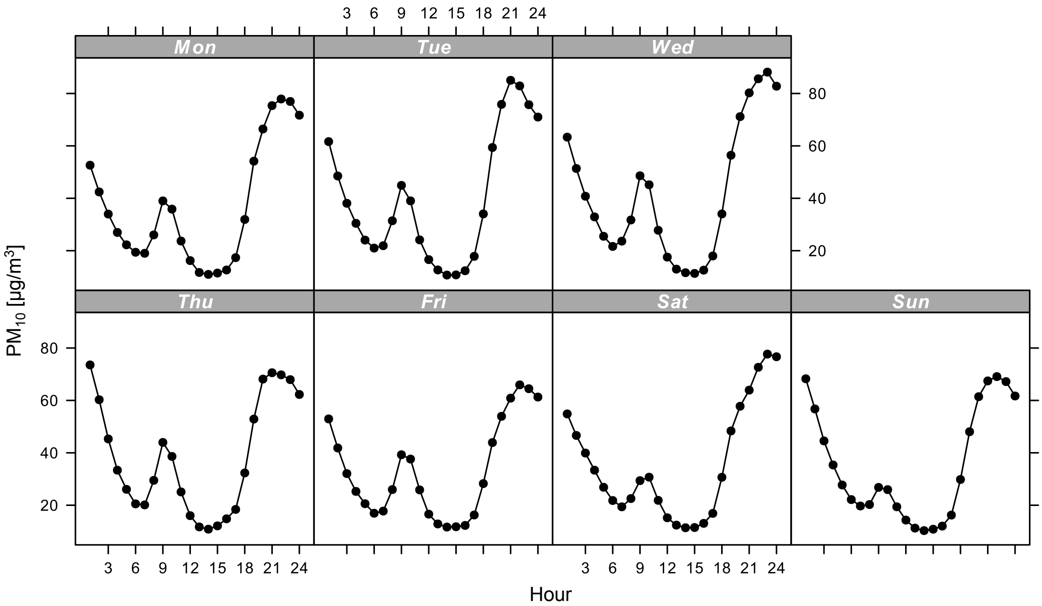

Figure 2.1: Average hourly PM_{10} concentrations at Coles Place by weekday, based on May - August, 1999 - 2008.

Section 4.3). These observations were recorded at the main air quality monitoring site in Christchurch, which is located at Coles Place in the suburb of St. Albans. A bimodal pattern is apparent in the concentrations with a minor morning peak at approximately 0900 hrs and a major peak in the evening at around 2100 - 2200 hrs. Both peaks reflect enhanced emission release during these times. The morning peak can be mostly attributed to rush hour traffic and industrial emissions, as indicated by the reduced concentrations during this period on the weekend, when work related traffic can be expected to be significantly lower. However, domestic heating emissions also contribute. The evening peak is mainly the result of increased emissions from home heating, whereas traffic emissions during evening rush hour also contribute. Thursdays, Fridays and Sundays show quite substantially lower concentrations during the evening, which most likely reflects influences of social activity, such as dining out, etc. In New Zealand, Thursday is traditionally pay-day, which may explain reduced PM_{10} levels similar to those on Fridays and Sundays. However, no robust explanation can be provided, so that the apparent difference in weekday evening peak concentrations remains speculative. Afternoons generally show low concentrations due to reduced emission activity and a well mixed atmospheric boundary layer.

The above mentioned source apportioning, together with the presented diurnal pattern of concentrations shows that, in order to tackle the problem, the focus of potential regulatory measures to decrease emissions needs to be on domestic sources. Various measures, such as bans of open fires, restrictions on burner installations for both new housing developments, as well as renovations along with monetary incentives such as interest-free loans for installation of heat pumps and similar clean heating devices, have seen mixed public reception in recent years. A detailed description of the proposed management options for air quality in Christchurch was provided by the Christchurch regional council (CRC) in their Natural Resources Regional Plan (CRC 2009). Cupples et al. (2007) provided an in-depth discussion on sociological factors such as cultural identity that underpin traditional home heating practices in Christchurch, and New Zealand in general. It seems, they argue, that even nowadays, the spirit of early colonial settlers is still deeply rooted in parts of Christchurch's population. This often results in reluctance to use modern heating, as it is part of New Zealand's heritage to endure cold winters through physical effort (e.g. wood chopping) but with minimal comfort. Another contributing factor, and also related to the aforementioned cultural issue, are old dwellings with mostly single-glazed windows and poor insulation.

2.1 Geography and local topography

Located on the eastern fringe of the Canterbury Plains, which slope gently from the coast to the Southern Alps, that rise to elevations well above 3000 m, Christchurch is a coastal city that is situated on generally flat terrain. However, immediately south of the main urban area, the Port Hills that form the northernmost side of the ancient volcanic landscape of Banks Peninsula, provide a local orographic feature that reaches elevations of up to 450 m (see Figure 2.2). Christchurch is the main urban centre of the Canterbury region, which is situated on the east coast of New Zealand's South Island.

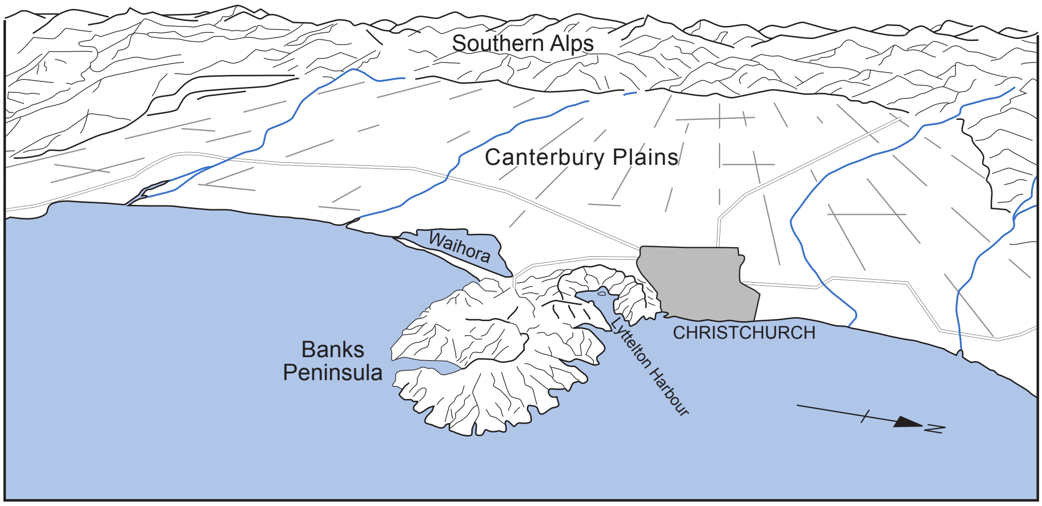

Figure 2.2: Schematic oblique view of the Canterbury region (from Sturman & Spronken-Smith 2001).

Apart from a higher density in high-rise buildings in the central business district, dwellings in the various suburbs are usually single storey houses. Furthermore, these houses are spread apart further than is usual in urban areas, so that the building density is rather low, when compared to other similar sized cities in the world. Christchurch also has a high amount of green space, as urban parks of various sizes are widespread and residential homes are generally surrounded by gardens. New Zealand itself is located in the mid-latitudes of the Southern Hemisphere, between 34° and 48° south and 166° and 179° east (Figure 2.3). Globally, this places New Zealand in the belt of mid-latitude westerly winds where warm subtropical air and cold antarctic air masses meet and frequently create frontal features that play a major role in New Zealand's synoptic weather patterns (Sturman & Spronken-Smith 2001, Sturman & Tapper 2006).

2.2 General climatology

The dominant feature that modifies the synoptic flow features over and around New Zealand are the Southern Alps, which form a generally perpendicular obstacle to the predominant westerly flow direction in the Southern

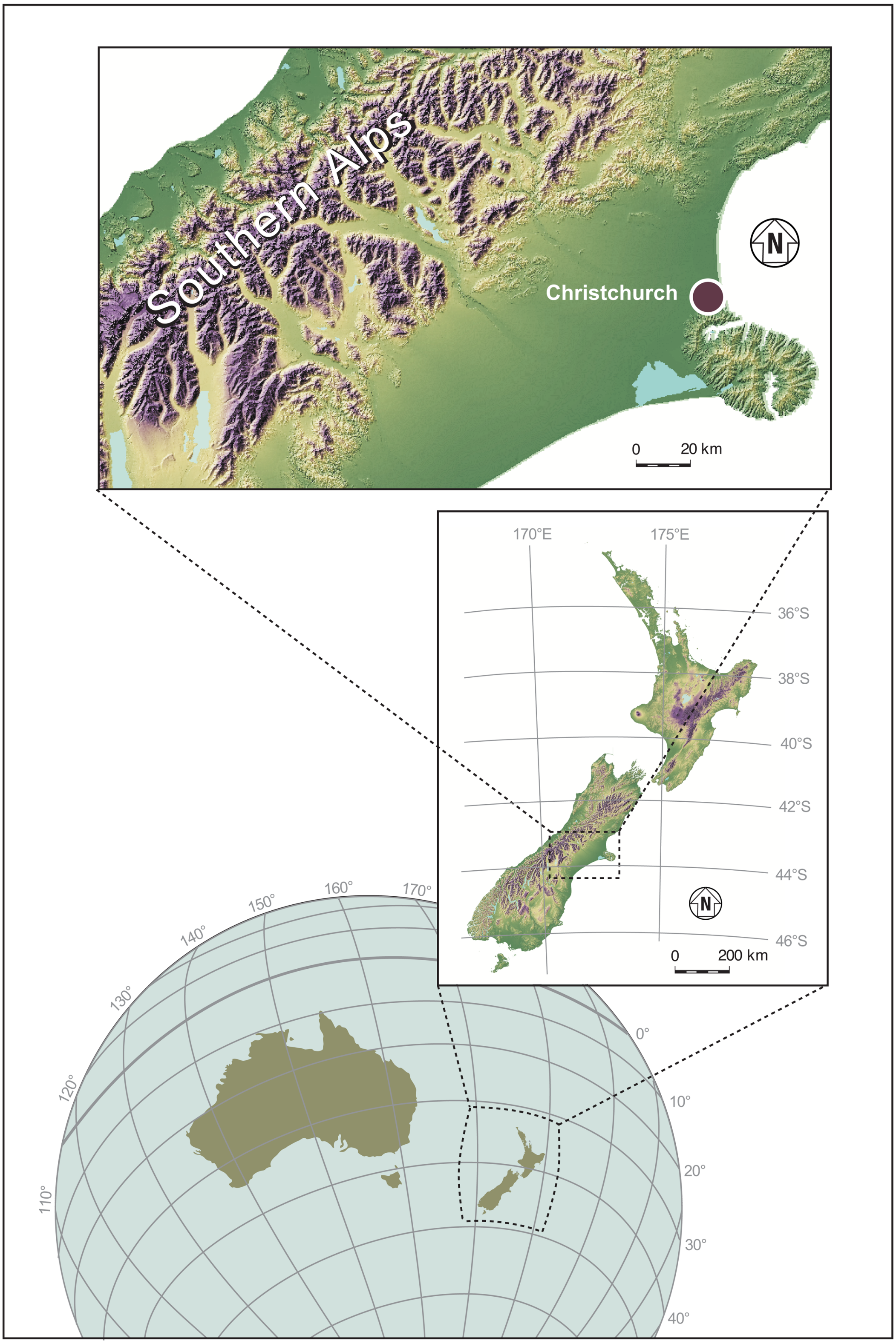

Figure 2.3: Map of New Zealand and the Canterbury region.

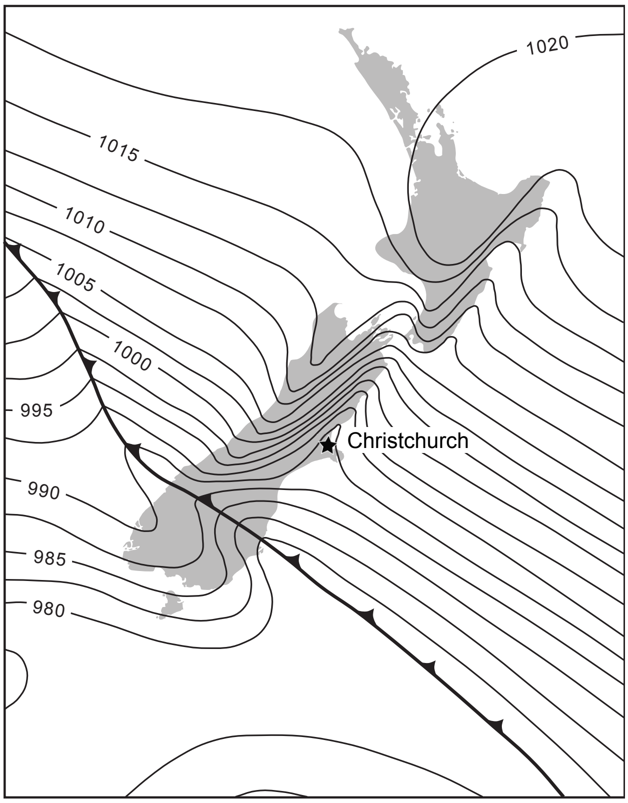

Figure 2.4: Disturbance of the surface pressure field due to orographic modification of north-westerly flow over the South Island. Modified from Sturman & Spronken-Smith (2001).

Hemispheric mid-latitudes. Figure 2.4 provides an example of a typical disturbance in the low level pressure field during a north-westerly gradient wind situation that results from orographic modification by the Southern Alps. A typical cold front approaching New Zealand from the south-west is also illustrated. These fronts are regularly split into a western and an eastern branch by the alpine barrier. The combination of westerly dominated surface flow and its modification by the Southern Alps results in a distinct reoccurring pattern of weather situations in the Canterbury region. Embedded in the mid-latitude westerlies, cyclonic and anticyclonic pressure systems and their associated frontal features, regularly cross New Zealand. Due to the alpine barrier, low level flow splitting and blocking are common features that modify gradient flow on both sides of the mountains. At Christchurch, possibly the most notable form of this modification is observed during north-westerly gradient flow conditions, when descending air over the Canterbury Plains is subject to dry adiabatic warming, resulting in very warm, and usually gusty foehn winds. These situations are often followed by the passing of a southerly to south-westerly cold front, replacing the warm air with cold antarctic air masses, and temperature drops of up to 15 K within one hour are not uncommon.

Even though synoptic flow in the region is dominated by westerly directions, surface winds that dominate Canterbury during the day usually show north-easterly directions. McKendry (1985) provided an extensive analysis of the complex mesoscale windfield in the region, with much focus on the 'Canterbury North-Easter'. Apart from the obvious, but generally rare occurrence of synoptic north-easterlies, he identifies three main processes that contribute to this regime. Firstly, the sea-breeze circulation in Canterbury is generally from the north-easterly direction, especially north of Banks Peninsula. Secondly, situations such as shown in Figure 2.4, regularly cause a local pressure gradient with relatively low pressure in the lee of the alps, so that the resulting compensation flow becomes north-easterly. A third component that adds to the phenomenon, is the recurving of air that is diverted around the South Island through Cook Strait (the marine passage separating New Zealand's North and South Islands) as a result of low level flow splitting (McKendry 1985, McKendry et al. 1987).

Further dominant low level flow in the Canterbury region is from south-west and west, the latter being most important at night. Figure 2.5 summarises the low level wind field as measured at Christchurch airport on a seasonal basis. The smoothing in this figure is done using the 'fields' package for R (Furrer et al. 2009). It is achieved by applying a kernel smoother to the matrix of frequency counts of wind direction (in bins of ten degrees) for each hour of the day. The kernel is defined as normal Gaussian and the bandwidth theta is set to $\vartheta = 2$. For further information refer to Furrer et al. (2009). The dominance of the day-time north-easterly regime is evident in this figure, especially during the summer season (DJF). As the focus of this study lies on winter time pollution, the season of interest for this research

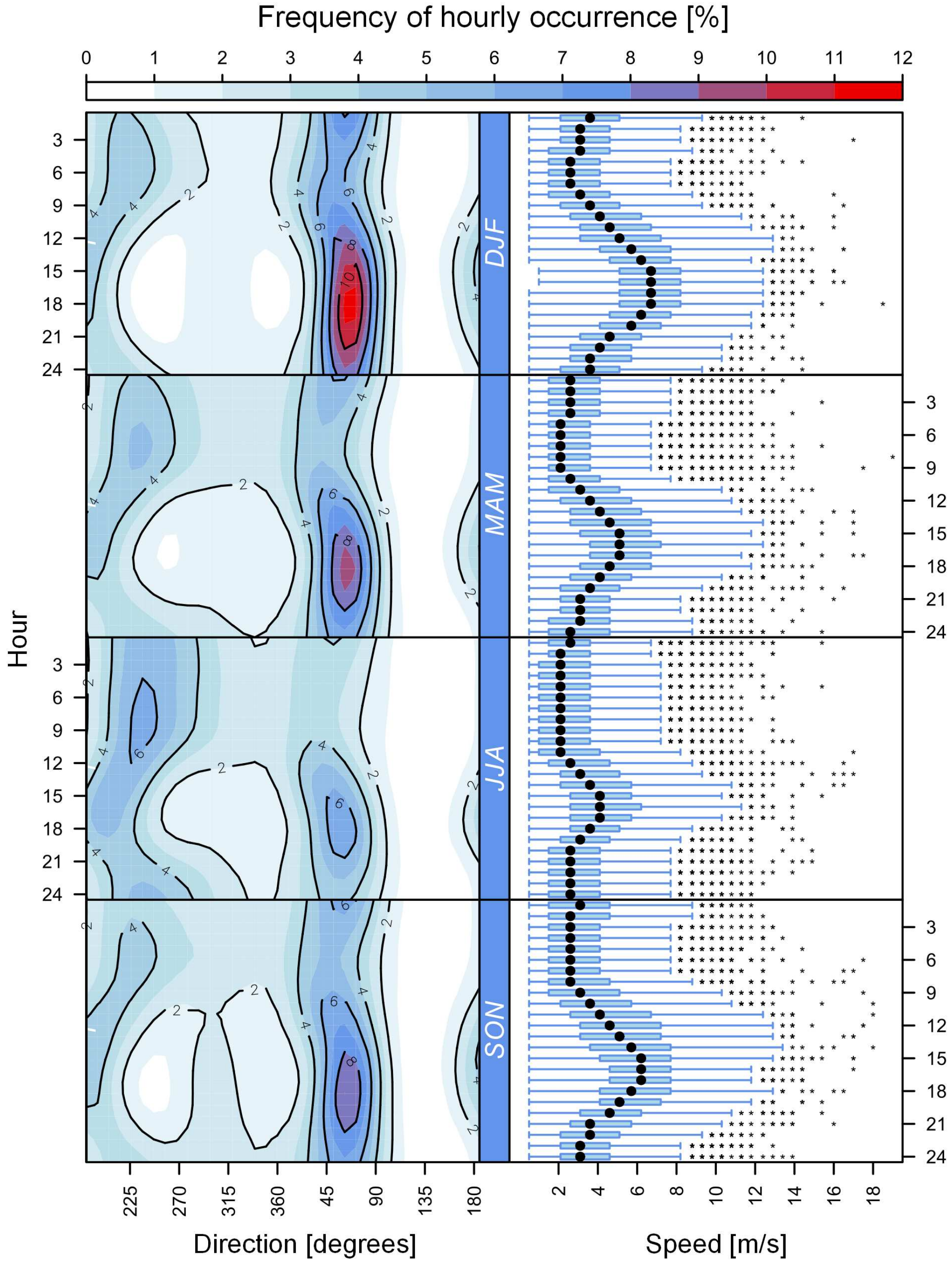

Figure 2.5: Seasonal variation in hourly wind direction frequency (contours and colour shading) and associated hourly wind speeds (box plots) at Christchurch airport for the period 1993 - 2008 (see central strip for labelling of seasons). Box plots show median (dot), interquartile range (box), 1.5 times the interquartile range (whisker) and outliers (*).

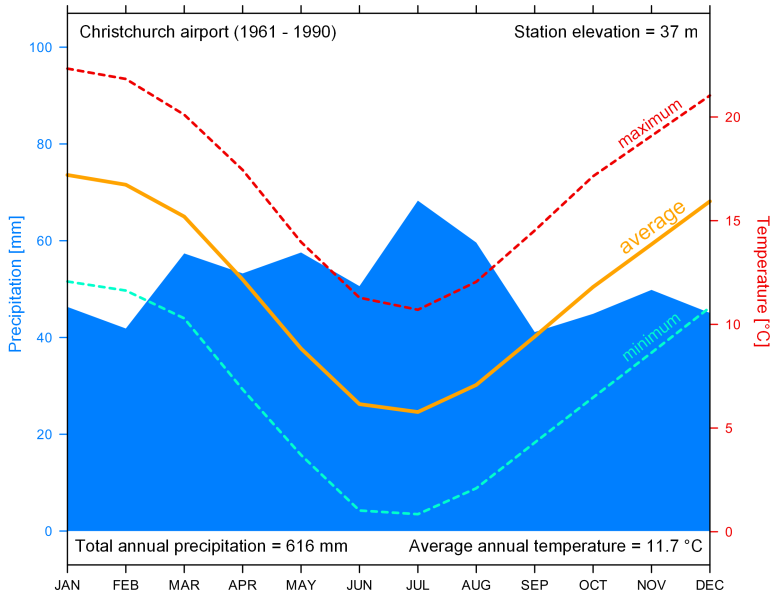

Figure 2.6: Climate diagram showing mean monthly precipitation sums (shaded blue), mean monthly maximum, average and minimum temperatures at Christchurch airport for the period 1961 - 1990.

is JJA. During this season, north-easterly frequency is decreased by almost half (in comparison to DJF) and day-time wind speeds are reduced. This is testament to the fact that reduced thermal forcing, as a result of shorter days and a higher solar zenith angle, decreases the sea-breeze component of the Canterbury North-Easter. This decrease is compensated by an increase in westerly to south-westerly flow, especially during the night. The increased nocturnal westerly flow component stems from enhanced cold air drainage from the Southern Alps into the city. As will become apparent in later chapters, this process plays a crucial role in influencing the dispersion potential of the stable night-time urban boundary layer in various ways.

A summary of the thermal and precipitation climatology of Christchurch is given in Figure 2.6. As can be seen, Christchurch shows no major seasonal rainfall signal. July and August are generally slightly wetter than the rest of the year, however, only marginally. Mean monthly temperatures show a clear seasonal variation with an amplitude of approximately 10 - 11 °C throughout the year. June and July are generally the coldest months and frost may happen regularly during this period (even though average minimum temperatures for these months are still slightly positive).

Generally, precipitation is low and, together with an average annual temperature of 11.7 °C, the climatology reflects New Zealand's maritime location in the temperate zone. In fact, according to Koeppen's climate classification, New Zealand exhibits a temperate oceanic climate (Cfb). Compared to the rest of New Zealand, however, precipitation amounts in Christchurch are at the lower end of the scale, which is a result of the rain shadow caused by the Southern Alps, which once more highlights the importance of this orographic feature for the climate of Christchurch, and New Zealand in general.

2.3 Air pollution meteorology of Christchurch

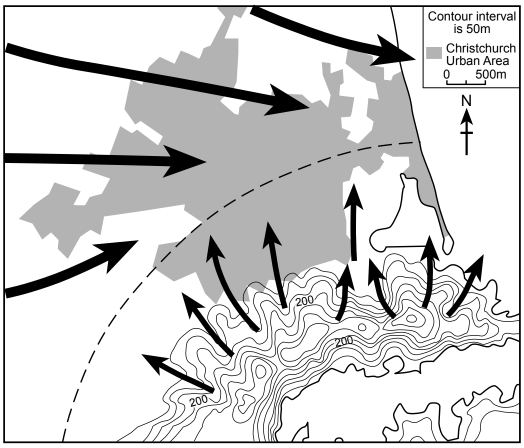

Figure 2.7: Schematic representation of dominant flow patterns and resulting flow convergence during smog nights in Christchurch (from Sturman & Spronken-Smith 2001).

As outlined in Section 1.1, air pollution in Christchurch has long been recognised as a significant problem. Until recently, however, only few investigations into meteorological controls of the problem have been carried out. About 50 years ago, a report published by the Air Pollution Advisory Committee (APAC) provided a brief section on meteorological conditions that lead to increased PM_{10} concentrations in Christchurch and provided a figure that depicts drainage of cold air from the Southern Alps into the city (APAC 1959). However, the information was kept very general and no mention of associated atmospheric processes was provided. Owens & Tapper (1977) analysed smog levels with regard to varying meteorological conditions at both local and synoptic scales and provided a first quantitative assessment of meteorological influences on pollution concentrations in Christchurch. Sturman (1985) provided a first comprehensive investigation of the influence of the mesoscale wind field on air pollution patterns during smog nights in Christchurch. Major progress in identifying meteorological control mechanisms on a local to regional scale has been achieved throughout the last decade. In particular, the aforementioned period of intensive atmospheric observations during winter 2000 (CAPS 2000) has enhanced the knowledge of the local air quality meteorology. Kossmann & Sturman (2004) and Corsmeier et al. (2006) identified that the local wind-field during smog nights regularly produces a stagnation zone over the city where katabatic winds from the alps meet the more localised drainage winds from the Port Hills (Figure 2.7). Timing and location of the stagnation zone vary throughout the night, but generally, drainage from the Port Hills is usually restricted to the southern parts of the city. Furthermore, McKendry et al. (2004) found that undercutting of cold, dense air from both the Port Hills and the Southern Alps regularly produces a very shallow katabatic layer that exhibits extremely stable atmospheric stratification close to the surface (depths ranging from 20 to 100 m). These situations may be exacerbated by warm on-shore north-easterlies aloft and/or north-westerly gradient flow on top of the low level flow. In fact, the complex three dimensional wind field over the region regularly produces multiple inversions above the urban area.

Due to the low building density of single storey houses and the high amount of green space, both the surface roughness of the city and its heat island effect can be expected to be lower than that of similarly populated cities in other parts of the world. The implications of this are that (a) day-time storage of thermal energy is reduced and hence, greater heat loss is observed at night, and (b) mechanical mixing is reduced. Both of these characteristics favour low level atmospheric stability, which in turn restricts dispersion and allows particulates to accumulate in the lower atmosphere.

For a city of its size, Christchurch provides a fairly unique example of particulate pollution in an environment that is dominated by emissions from solid fuel burning for home heating. Thessaloniki in Greece, a city of comparable size, also suffers from winter time PM_{10} pollution. General geography (coastal location), local topography of complex terrain and climate (at least during the winter months) are quite similar to the local set up in Christchurch, however, the main emission contribution stems from traffic, not domestic fires (Manoli et al. 2002, Slini et al. 2006). A location dominated by home heating emissions is Launceston, Tasmania. Source contribution of domestic emissions is similar to that of Christchurch (Gras et al. 2001, Luhar et al. 2006), however, the city is smaller and located some distance away from the coast.

Chapter 3

PM_{10} concentrations and local meteorology

3.1 Introduction

This chapter provides an assessment of meteorological controls on PM_{10} concentrations at the local scale. Atmospheric variation and its influence on air quality is assessed through analysis of 10 years of PM_{10} observations between 1999 - 2008 from one single air quality measurement site in Christchurch. Section 3.2 provides a classification analysis of local meteorology with regard to its potential to degrade air quality and evaluates trends in concentrations over the monitoring period with the impact of meteorological variability reduced. This is followed by an alternative approach to identifying a meteorologically adjusted pollution trend in Section 3.3.

This chapter is probably the most relevant to local authorities, as the results presented here provide a direct evaluation of the efficacy of policies that have been implemented over recent years by revealing concentration trends that are not obscured by variations in atmospheric conditions. Furthermore, it introduces a straightforward and repeatable approach to effectively classifying and therewith quantifying local meteorological conditions that show varying degrees of potential to degrade air quality in Christchurch. This classification can then lay the foundation for further applications, such as historical air quality analysis and short-term pollution forecasting, as discussed in later chapters of this thesis.

3.2 Assessment of exceedence potential

3.2.1 Introduction

This section investigates pollution potential as controlled by local atmospheric conditions. The main aim of this section is to provide a quantification of daily exceedence probabilities for the air quality monitoring period between 1999 - 2008 as a result of variations in local meteorology. The main method used in this section is classification tree analysis that allows every day to be assigned an exceedence probability based on local atmospheric conditions. It provides a clear quantification of atmospheric parameters that lead to the identified exceedence probabilities. Results are arranged into a decision tree diagram which allows for easy interpretation. This approach enables assessment of year-to-year variation in meteorologically controlled pollution potential through time series analysis of exceedence probability class frequencies. This then provides means to assess trends in PM_{10} concentrations in recent years by enabling investigation of pollution levels independent of meteorological conditions (or more precisely within classes of similar meteorological conditions). Trend assessment of air quality in New Zealand has only been established in recent years (e.g. Appelhans et al. 2007, Scarrott et al. 2009), as continuous quality controlled observations have only recently accumulated to data sets large enough to enable such analyses.

An extensive body of research exists that describes the effect of meteorological control mechanisms on pollution transport and dispersion in a general manner (e.g. Oke 1987, Arya 1999, Zawar-Reza & Spronken-Smith 2005). Furthermore, numerous studies have investigated local atmospheric influences on air quality for a vast range of pollutants and locations around the world, including Christchurch (e.g. Kossmann & Sturman 2004, Corsmeier et al. 2006, Elminir 2005, Wise & Comrie 2005*b*, Zawar-Reza et al. 2010). Owens & Tapper (1977) investigated meteorological influences (including synoptic influences) on various pollutants in Christchurch. They found that at the local scale "correlation of individual meteorological parameters with pollution levels was not strong, with temperature and wind speed being the most important" (Owens & Tapper 1977, p. 35). They also stated that "considerable refinement in both data used and method of analysis is possible" (Owens & Tapper 1977, p.35). The analysis in this section addresses both of these issues. Instead of using classical correlation and regression approaches as used by Owens & Tapper (1977), a classification based approach is taken here that incorporates meteorological data obtained at higher temporal resolution than utilised by them. This allows not only identification of relevant relationships between meteorological conditions and PM_{10} concentrations, but also provides detailed quantitative information on local pollution potential in response to varying combinations of meteorological parameters.

3.2.2 Classification of exceedence potential

Classification tree analysis is used to classify the local meteorology that influences air quality in Christchurch. Classification and Regression Trees (CART) describe a statistical procedure that was introduced by Breiman et al. (1984). CART have been applied to a wide variety of environmental studies, including air quality problems. Zheng et al. (2009) successfully identified several management options that influence yield variability of soy bean crops in Northeast China under drought conditions and showed that these can be more influential than ecological factors, such as regulating soil parameters. In Canada, Waheed et al. (2006) evaluated CART in its usefulness to identify different crop management strategies through hyperspectral remote sensing techniques and showed that the classification tree approach yielded 75% - 100% classification accuracy. Hendrikx et al. (2005) used CART to develop an avalanche forecasting scheme in an extreme maritime climate (Fjordland, New Zealand) based on various lagged and non-lagged meteorological parameters that enabled prediction accuracies of up to 86%. Slini et al. (2006)

evaluated 4 different statistical techniques to forecast PM_{10} concentrations for Thessaloniki, Greece and concluded that CART proved satisfactory in capturing concentration trends.

A brief summary of the method used in this section is given below. For an in-depth description of the recursive partitioning algorithm used in this study refer to Hothorn et al. (2006). Based on a set of predictor variables, this statistical approach uses recursive partitioning to split the response into a set of classes (nodes) with maximum class purity and arranges the final splits into a decision tree diagram. At each stage of the partitioning, all possible splits are identified using a Monte Carlo approach. For each potential split a p-value is calculated using a suitable statistic (depending on the nature, notably the statistical scale, of the predictor variable) to ensure comparability of the split criteria. Finally, a split is made to produce exactly two nodes using the predictor with the lowest p-value. Each of these nodes then becomes the input and the procedure is repeated as outlined above. In order to avoid over-fitting of the classification tree, it is possible to control for minimum node size, i.e. the minimum amount of observations the resultant nodes must have after each split. Furthermore, the p-value for possible splits can be specified so that splits are only allowed if the split-statistic is significant at a p-value lower than the specified level.

In a conservative set up (minimum final class size was set to 100 observations and splits were only allowed at p-levels < 0.001), approximately 1200 daily observations from the years 1999 - 2008 of the binary response as to whether the national guideline of 50 $\mu g/m^3$ was breached or not (exceedence yes/no) were regressed against a wealth of predictor variables (see Table 3.1). Such a conservative approach was chosen in order to assess general influential conditions rather than identifying statistical characteristics that are unique to the investigated data set. Furthermore, this conservative set up addresses the issue of over-fitting, even though the utilised algorithm was explicitly developed by Hothorn et al. (2006) to avoid this well known issue of CART applications. In fact, they concluded that the development of their unbiased recursive partitioning algorithm addresses all previously problematic issues of CART, so that post-classification measures such as pruning and

Table 3.1: Predictor variables for classification tree analysis.

Variable name	Description [measurement unit]
Tmin_i1	Minimum temperature of the following day [°C]
Tmax_i_Tmin_i1	Difference between maximum temperature of considered day and minimum temperature of following day [K]
ws_00_06	Mean wind speed between 0000 hrs and 0600 hrs [m/s]
ws_06_12	Mean wind speed between 0600 hrs and 1200 hrs [m/s]
ws_12_18	Mean wind speed between 1200 hrs and 1800 hrs [m/s]
ws_18_24	Mean wind speed between 1800 hrs and 2400 hrs [m/s]
ws_00_12	Mean wind speed between 0000 hrs and 1200 hrs [m/s]
ws_12_24	Mean wind speed between 1200 hrs and 2400 hrs [m/s]
ws_18i-1_24i-1	Mean wind speed between 1800 hrs and 2400 hrs of preceding day [m/s]
ws_18i-1_06	mean wind speed between 1800 hrs of preceding day and 0600 hrs of considered day [m/s]
rh	Relative humidity at 0900 hrs [%]
p	Mean sea-level pressure at 0900 hrs [hPa]
p_i-1_i	Difference in mean sea-level pressure at 0900 hrs between preceding day and considered day [hPa]
rad	Daily global radiation [MJ]
rain	Accumulated 24h rain [mm]

cross-validation become redundant. Analysis was restricted to winter months (May – August) as this is the period when most of the yearly exceedences occur. Air quality observations were collected at the main air quality site in Christchurch at Coles Place, whereas meteorological data was taken from Christchurch airport. Using predictor and response variables from different sites is not ideal, but was necessary so that the identified relationships can be used to serve as proxies for an assessment of historic air quality variability in Christchurch (Christchurch airport has a much longer climate record). For an assessment of site comparability with respect to atmospheric conditions refer to Figure 3.8 in Section 3.3. To account for the fact that atmospheric processes are not restricted to any regulatory period, lagged information of several meteorological variables was also considered, as is standard procedure in time series analysis. Given that this analysis is to provide the basis for an investigation of pollution potential over past decades, input data were limited to observations that were available at daily or higher temporal resolution. This is true for all variables listed in Table 3.1. Unfortunately, information on vertical atmospheric structure was not available at satisfactory temporal resolution. However, in an attempt to approximate nocturnal atmospheric stability, information on the cooling rate between the maximum temperature of the considered day and the minimum temperature of the next day was taken into account *(Tmax_i_Tmin_i1)*. Missing data are not allowed for classification tree analysis. Therefore, all days with missing observations in any of the listed variables were excluded from the analysis. However, missing data becomes an important issue when assessing historical variations in exceedence potential and a comprehensive discussion on this is provided in Section 5.2.

Using a binary categorical response has a few distinct advantages over using continuous data such as PM_{10} concentrations. Firstly, the variance that is to be predicted is kept at a minimum. Secondly, interpretation of the results is straightforward as the distribution within each final class represents the probability of exceeding the national standard under a given meteorological scenario.

Based on the outlined inputs, the algorithm produced a classification tree with five terminal nodes [see Figure 3.1 - note that terminal nodes (TNs) were manually relabelled according to their pollution potential from high to low for ease of interpretation]. Out of the comprehensive set of potential predictors, three variables were found to be most significantly influential to split the response into the identified classes. These are minimum temperature of the following day (split 1 - depicting whether a given night is a frosty night or not), average wind speed between 1200 hrs and 2400 hrs (split-level 2) and average wind speed between 1800 hrs and 2400 hrs (split-level 3). As particulate pollution in Christchurch stems mostly from domestic fires, temperature can be considered as a key driver behind emission release, and wind speed governs dispersion of pollutants to a high degree, especially as no information of atmospheric stratification is available. At a general level, the meteorological conditions for each identified terminal node can be summarised as follows (note that 'morning' refers to morning of the following day as identified by *Tmin_i1*):

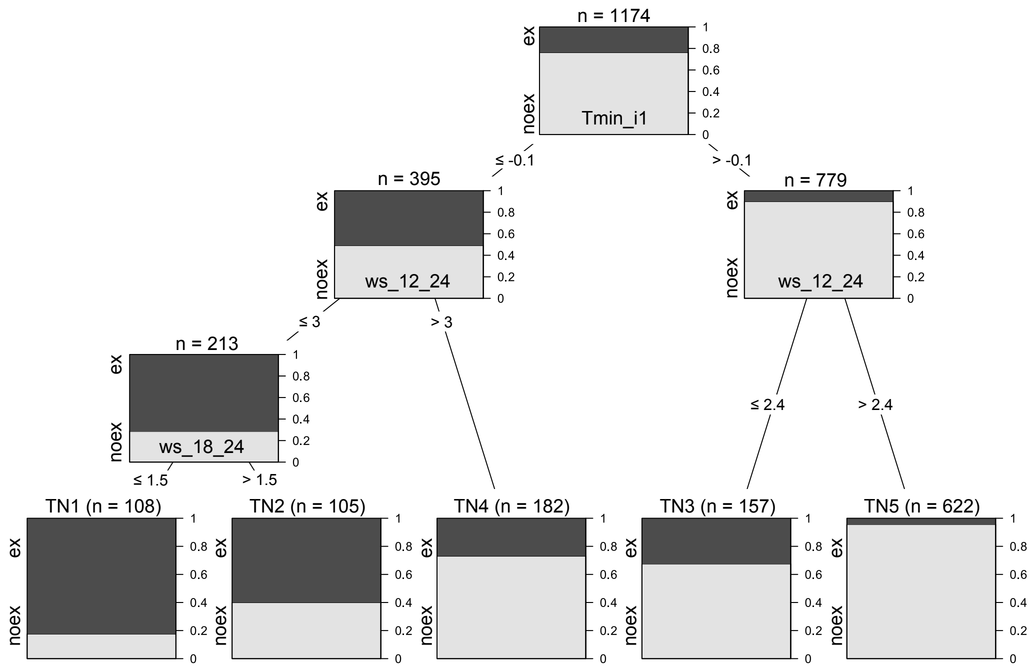

Figure 3.1: Classification tree assigning each day into an exceedence probability class (terminal node - TN). Meteorological variables used to apply splits are shown in inner nodes. n denotes the number of observations in each node (inner and terminal), while the dark shaded sections labelled 'ex' represent proportion of exceedences and the light shaded sections labelled 'noex' represent the proportion of no-exceedence days.

TN1 calm conditions during the second part of the day, extremely calm conditions during the evening, frost in the morning.

TN2 similar to TN1, though no major calming effect during the evening.

TN3 calm to very calm conditions during the afternoon and evening, no frost in the morning.

TN4 frost in the morning, windy conditions during the day.

TN5 no frost, windy.

The first two terminal nodes represent conditions that are likely to result in degraded air quality. Meteorological conditions as identified by terminal node 5 clearly promote good air quality, and the remaining two classes can be described as intermediate. Terminal node 5, the class with lowest pollution potential, accounts for approximately 50% of the original data (622 out of 1174 days). The remaining terminal nodes represent between 10% and 15% each of the input data (remember that minimum node size was set to 100 observations). Each of the terminal nodes represents a distinct class of meteorological conditions in the sense that overlaps are not possible. For example, terminal node 4 includes all days where minimum temperature of the following day does not exceed -0.1 °C and wind speed between noon and midnight averages to more than 3 m/s. As mentioned earlier, having a binary response variable enables direct assessment of pollution potential of each terminal node. The probability of an exceedence occurring under meteorological conditions as characterised by TN5 is 0.04. On the other end of the scale, 82% of all days with an atmospheric set up as described by TN1 will see a breach of the national air quality standard for PM_{10}.

3.2.3 Air quality and governing local meteorological characteristics

The diurnal surface climatology of the identified terminal nodes is summarised in Figure 3.2. It shows hourly wind direction frequencies in percent along with corresponding hourly average wind speeds (left) and temperatures (right) at Christchurch airport for each class. As in Figure 2.5, smoothing of contours is implemented using the 'fields' package for R (Furrer et al. 2009; contour lines are smoothed using $\vartheta = 2$, colour contour shading is smoothed using $\vartheta = 1$).

The generally increasing wind speeds from low to high pollution classes are testament to the fact that the classification is to a large degree based on wind speed conditions (during the second part of the day). The general temperature distribution across the nodes also reflects the underlying classi-

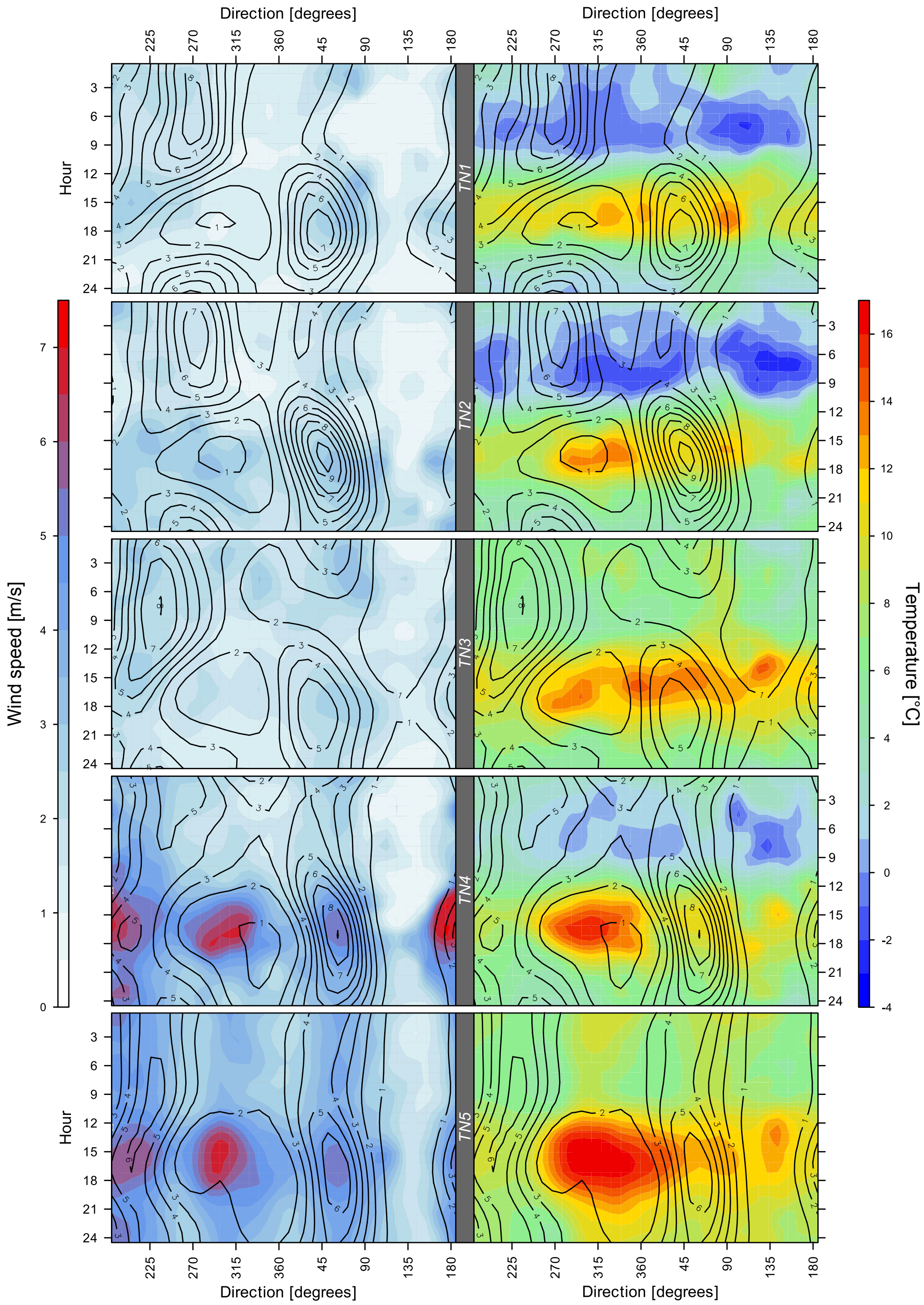

Figure 3.2: Contour plots of hourly wind direction frequency in percent (contour lines) by TN (see central strip for labelling) at Christchurch airport for the months May - August, 1999 - 2008. Colour contours show average hourly wind speeds (left panels) and average hourly temperatures (right panels) with regard to wind direction. Number of days that these plots are based on is 108, 105, 182, 157 and 622 for TN1, TN2, TN3, TN4 and TN5, respectively (see Figure 3.1).

fication (the primary split is based on temperature), so that TNs 1, 2 and 4 describe colder conditions than TNs 3 and 5. With regard to general wind flow patterns, it becomes evident that, for TNs 1, 2 and 4, the dominant flow direction during the (late) afternoon is north-east, whereas TNs 3 and 5 show increased frequencies of south-westerly flow directions. Partly due to the flow obstruction by Banks Peninsula, flow from the south-east is generally rare, occurring less than one percent of the time. With TNs 1 - 4 being comprised of less than 200 days in total, this means approximately one, sometimes two hourly occurrences. Furthermore, many of the values in this south-easterly range are artificial in the sense that they result from smoothing over missing values and will therefore not be interpreted, as no solid conclusions can be drawn from this. Given below is a summary of the atmospheric conditions that are represented by each of the TNs at a more detailed level than the one that was given earlier.

TN1 *Wind field:*

A clear diurnally reversing flow pattern is evident. Flow during the second part of the day is generally from north-east with a maximum in frequency in the early evening (1800 hrs). Windiest conditions during the day are found in the afternoon (1200 hrs - 1800 hrs) under easterly- to north-easterly flow. Day-time southerly flow is also frequent which tends to be associated with increased wind speeds. Nocturnal flow is generally from westerly directions with equally frequent deviations to south-westerlies (windier) and north-westerlies (calmer). This usually lasts until mid-day with a maximum frequency of occurrence between 0300 hrs and 0900 hrs. A general tendency for flow to switch from north-easterlies to westerlies in the evening is observed. The timing seems to be variable, but it is indicated that this transition is likely to happen between 2100 hrs and 2400 hrs.

Thermal conditions:
Day-time temperatures are highest during easterly, northerly and north-westerly flow with temperatures reaching >10 °C between 1500 hrs and 1800 hrs. North-easterlies, westerlies and south-westerlies are generally associated with cooler conditions. Day-time north-westerlies in Christchurch are generally depicting warm (and usually gusty) foehn winds. However, due to the relatively low wind speeds associated with these conditions in TN1, it is indicated that this foehn is not fully developed under the conditions described by TN1 (this is also the case for TNs 2 and 3). Owens & Tapper (1977) identified undeveloped north-westerly flow as one of the synoptic situations that are associated with elevated levels of pollution. Due to the more continental air-mass character, night-time cooling is accelerated during north-westerly flow and alleviated under north-easterly conditions. Apart from during north-easterly and southerly flow, night-time temperatures regularly fall below the 0°C mark.

TN2 *Wind field:*
The general diurnal pattern is similar to conditions described by TN1. However, differences are apparent. Duration and frequency of the day-time nor' easter is enhanced. The onset is brought forward by a few hours, as well as the peak in occurrence, which is slightly shifted forward to around 1600 hrs to 1700 hrs. Frequency of north-easterlies is increased at the expense of southerly to south-westerly flow during the afternoon. Even though still predominantly from the west, nocturnal flow is less dominated by westerly to south-westerly flow directions and shows increased frequencies of north-easterly flow, which provides additional evidence of the increased importance of north-easterlies under conditions described by TN2. As a result of this, the transition between day-time easterly and night-time westerly flow direction occurs less frequently and also tends to be delayed.

A comprehensive analysis of the transition meteorology and its effects on pollution dispersion will be presented at a later stage in Chapter 4. Increased day-time wind speeds are also slightly delayed (1600 hrs - 2000 hrs) and are usually associated with north-easterly and westerly flow conditions.

Thermal conditions:
Diurnal temperature variation is very similar to TN1. One major difference however, is the enhanced night-time cooling. Evening conditions tend to be slightly warmer, whereas early morning hours generally show lower temperatures, independent of flow direction (remember that south-easterly flow is not being considered here). This becomes important with regard to air pollution dispersion, as higher nocturnal cooling rates indicate enhanced thermal stability of the atmosphere. This will be analysed and discussed in more detail in Chapter 4.

TN3 *Wind field:*
A diurnal pattern is still observable, but day-time north-easterlies are less frequent. Nocturnal winds exhibit an increased south-westerly component. The transition between day-time and night-time flow is likely to happen even later. Wind speeds are generally low, but the diurnal signal is weaker, and nocturnal flows do not reduce to the same effect as for TN 1, especially under southerly and north-easterly flow.

Thermal conditions:
Conditions described by TN3 show a very damped diurnal signal in temperatures, especially as nights tend to be fairly mild. Day-time values are generally increased when compared to the previous nodes. Apart from south-westerly to southerly flow, which is slightly cooler, day-time temperature values show relatively uniform distribution across all flow directions. Similar to

previous TNs, flow from easterly to north-easterly directions is associated with the mildest conditions.

TN4 *Wind field:*

With regard to air flow direction, the diurnal signal is decreased in comparison to previous nodes. Wind speeds, however, reveal a very clear diurnal pattern, with distinct afternoon maxima for flow from southerly, north-westerly and north-easterly quadrants. The two most dominant flow regimes are south-westerlies and north-easterlies, the latter being more dominant than the former and showing a slight increase in the easterly component when compared to previous TNs. Transitions between them are less likely, and when occurring, they tend to happen earlier in the morning and later at night. Nocturnal flow from the north can be weak.

Thermal conditions:

In comparison to TN3, TN4 generally describes colder conditions, especially at night. Flow from the north-west shows highest temperatures during the day, which, in combination with the highly increased wind speeds associated with this flow direction, indicates fully developped foehn wind occurrence (as opposed to the less developped foehn winds in previous nodes). Night-time cooling tends to be accelerated under north-westerly conditions, however, early morning temperatures under northerly to north-easterly flow are also rather cool.

TN5 *Wind field:*

A similar pattern to TN4 is apparent with regard to both flow direction and wind speeds, whereas the diurnal signal in direction is even weaker. In fact, the flow conditions are such, that the two most dominant flow regimes, namely south-westerly and north-easterly, are likely to remain stable throughout the course of the day, with transitions between them only occurring rarely.

Increased day-time wind speeds are found during south-westerly, north-easterly and north-westerly flow, with the latter being the windiest of conditions. This, in conjunction with the high temperatures associated with this flow, again depicts fully developed gusty and warm foehn winds. Nocturnal flow is weakest under westerly, northerly and south-easterly conditions (TN 5 is comprised of 622 days, so that interpretation of south-easterly flow seems reasonable).

Thermal conditions:
The above mentioned weak nocturnal flow is associated with the lowest temperatures in this TN. North-westerly and easterly flow shows the warmest/mildest conditions during day-time/night-time. Day-time south-easterlies can also be associated with elevated temperatures.

In summary, Figure 3.2 provides a great deal of detailed information on the local meteorology that is associated with different levels of air quality and reveals some important features. Firstly, conditions that are conducive to producing high levels of PM_{10} concentrations (TN1 & TN2) are much more clearly governed by a diurnally reversing flow regime with night-time westerlies and day-time north-easterlies. Secondly, under conditions that tend to enhance local air quality, nocturnal flow is more frequently dominated by south-westerly winds as opposed to the truely westerly or even north-westerly directions in the high pollution classes. Diurnally reversing flow with a true westerly nocturnal component in the high pollution nodes indicates a process described in Kossmann & Sturman (2004). During smog nights, dense, cold katabatic winds drain from the Southern Alps across the Canterbury Plains in a general north-westerly flow and get split by Banks Peninsula, so that north of the peninsula (over Christchurch) a more westerly flow component is observed. South-westerly flow over Christchurch, however, is usually associated with true south-westerly synoptic flow. If this is weak, a nocturnal transition to westerly or north-westerly flow may be observed in

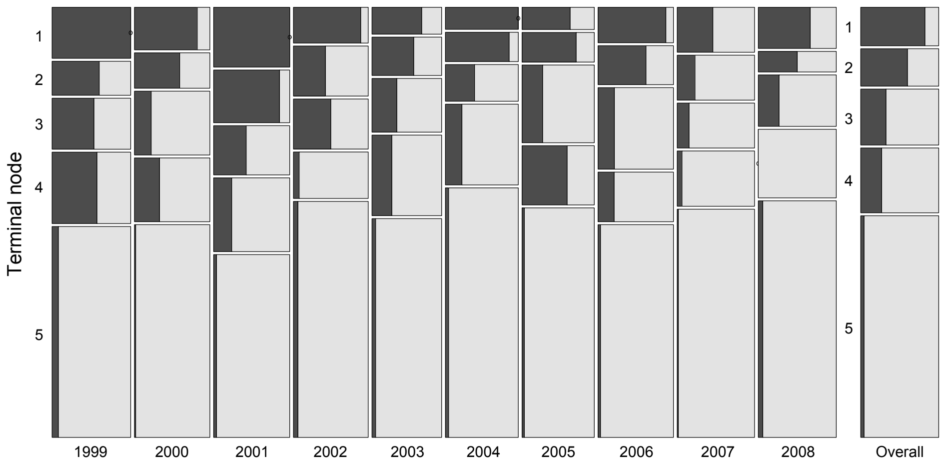

Figure 3.3: Frequency of terminal nodes between 1999 - 2008. Vertical distribution shows frequency of terminal nodes per year. Horizontal distribution shows frequency of exceedences (dark grey areas) per node.

Christchurch. This, however, is a rather rare phenomenon. Therefore, it can be expected that the identified classification reflects low level flow that originates from different processes at both meso- and synoptic scales. Further analysis at both scales is provided in later chapters.

Along with the overall distribution of terminal nodes (right panel), Figure 3.3 shows the distribution of the identified TNs vertically for each year between 1999 - 2008. Additionally, horizontal frequencies denote the proportion of exceedences that occurred within each node in each year (dark grey areas). Year-to-year variability is high. However, apart from TN1 and TN5, a clear decrease in the amount of exceedences is indicated. Additionally, this figure is not taking into account absolute concentrations, which are likely to provide a better basis for trend assessment, as continuous data is more sensitive to changes than factorial (in this case binary) data. However, by simple visual examination, it becomes obvious that towards the end of the record, light grey colours are clearly increasing, regardless of the distribution of exceedence probability classes. However, deviations of this trend are still apparent, e.g. the high amount of exceedences within TN4 in 2005. Nonetheless, a clear indication of a downward trend is found, which will be investigated further in the following section.

3.2.4 Trends in PM_{10} concentrations under similar local meteorology

The results presented in Section 3.2.2 enable assessment of the trend of PM_{10} concentrations with the influence of meteorological variability reduced, as it allows comparison of PM_{10} concentrations over time within each meteorological class (TN). Even though fundamentally achieving the same result (a reduction in the influence of meteorological variability to get a better approximation of emissions), the approach taken in this section is different from the analysis outlined in Section 3.3 and is, in many ways, much more straightforward. Apart from data transformation to get a reasonably normally distributed data set, no other pre-processing is needed (provided the data has already been classified as outlined above).

In order to assess trends in both central tendency and upper extremes, regression analysis was carried out for median values and 90$^{\text{th}}$ percentiles. As pollution concentrations are usually highly skewed (Ott 1990, Giavis et al. 2009), their distribution and possible transformations need to be assessed before any parametric statistical procedure can be applied. Figures 3.4 and 3.5 give an overview of data distribution for PM_{10} concentrations for each terminal node (upper panels). Even though division into classes reduces skewness, observations within each terminal node are still positively skewed (for comparison the overall distribution of PM_{10} concentrations is shown on top of the panels in Figure 3.4). Therefore, they were transformed using both the square root (central panels) and logarithm (lower panels) and respective normality was assessed using the Anderson-Darling test for normality (Anderson & Darling 1952). The p-values obtained by this test are shown in each panel of Figure 3.5. The lower a p-value, the further a given distribution deviates from normal Gaussian. Inspection of the transformations reveals that both greatly enhance normality of the distribution. The square root transformed values still exhibit a slight positive skew (see reduced curvature of point cloud in Figure 3.5). The log transformation on the other hand, slightly over transforms the data and produces a slight negative skew (see concave curvature of point cloud in Figure 3.5). It also increases kurtosis of the distributions.

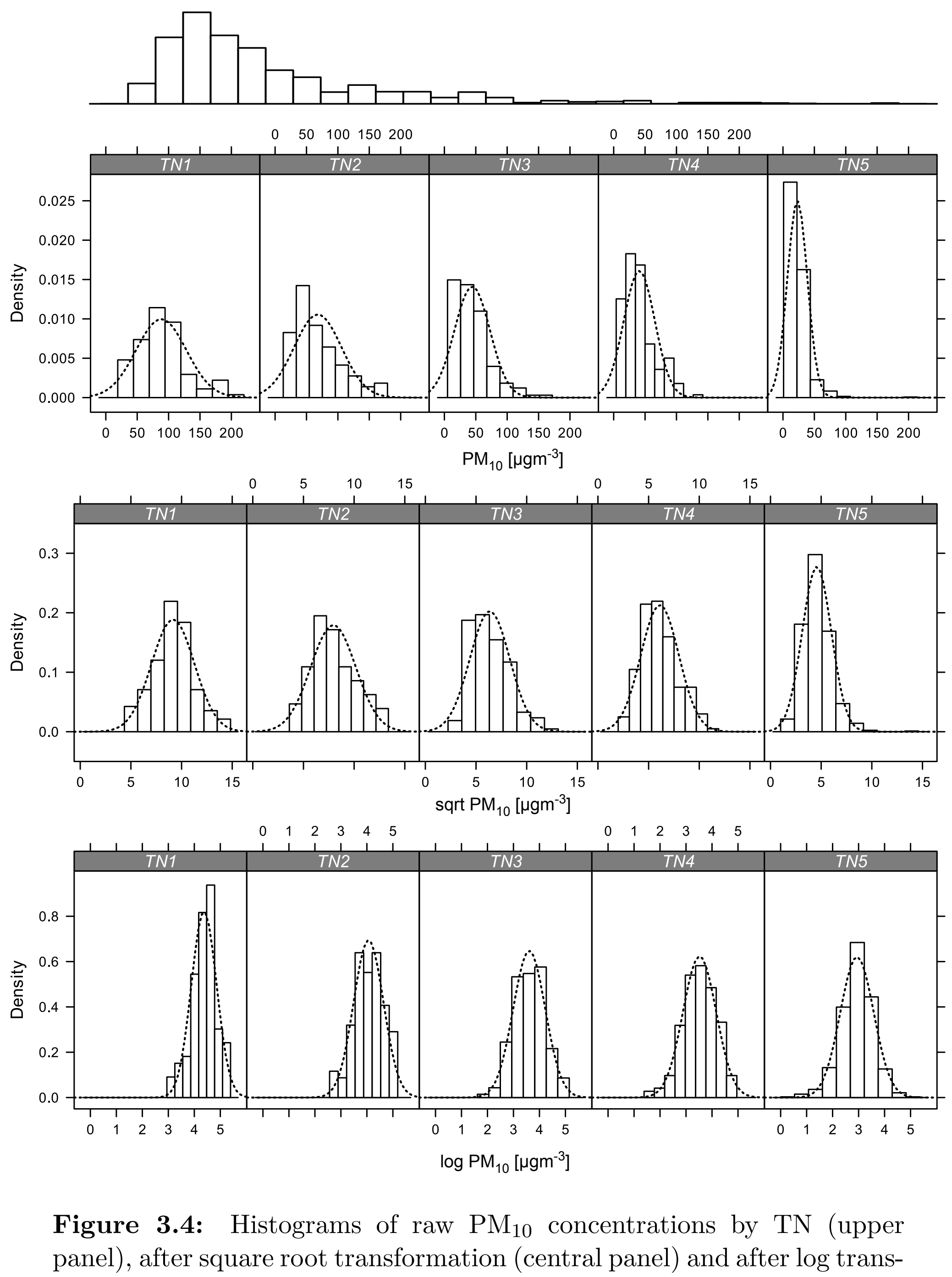

Figure 3.4: Histograms of raw PM_{10} concentrations by TN (upper panel), after square root transformation (central panel) and after log transformation (lower panel). Dashed lines denote theoretical normal Gaussian density distribution for observed mean and standard deviation in each TN. The overall distribution of PM_{10} concentrations is shown above top panel as a reference.

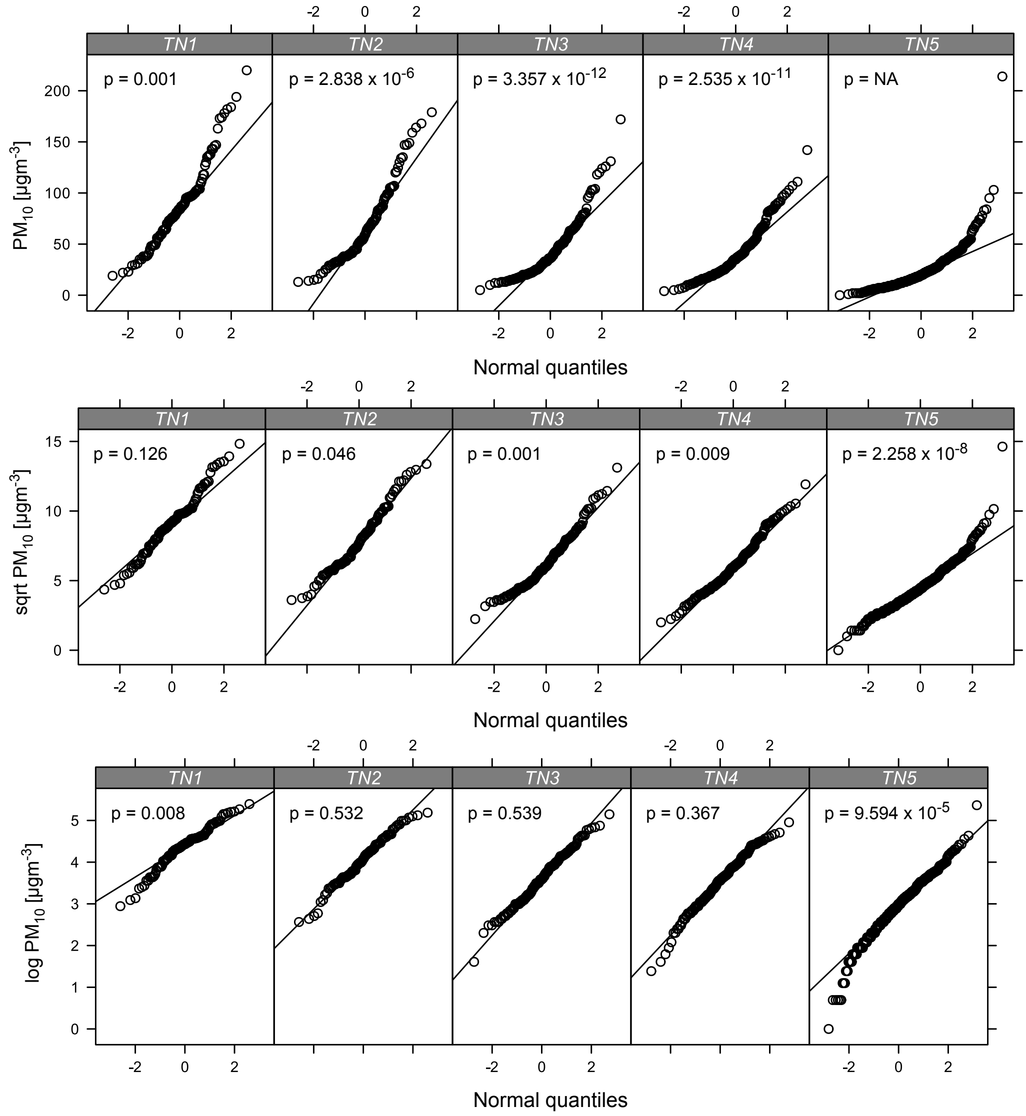

Figure 3.5: Quantile-quantile plots of PM_{10} concentrations versus normal quantiles by TN for raw concentrations (upper panel), after square root transformation (central panel) and after log transformation (lower panel). The p-value of the Anderson-Darling test for normality (Anderson & Darling 1952) is shown in top left corner of each panel.

Given that the square root transformation performs best in the terminal of highest interest, TN1, it was decided to carry out the regression analysis on the basis of the data that was transformed using the square root, even though the logarithm achieves a better approximation of a normal distribution in the remaining TNs.

The results of the regression analysis of 90^{th} percentile and median PM_{10} concentrations over time for the period 1999 - 2008 are shown in Figure 3.6. In both cases, significant trends, as denoted by the p-levels for the slope of the regression line (top right corner in each panel), can be found for the first three terminal nodes. Given the small sample size of only ten observations, one for each year, confidence of the trend in each panel is low, as indicated by the wide spread between upper and lower confidence levels. Furthermore, a high amount of scatter can be seen in some meteorological classes which may indicate that substantial residual meteorological variability is still apparent within terminal nodes. Some of the observed variability in concentrations, however, will stem from socio-economically driven human behaviour patterns which cannot be expected to be constant over time. For example, usage of solid fuel burning may vary according to the price of electricity and/or the fuel used. Overall, a downward trend in particulate levels over time is apparent for all TNs apart from TN5 which describes meteorological conditions that are not expected to deteriorate air quality anyway.

It is very encouraging to see that concentrations measured under meteorological conditions that show the highest potential for producing elevated PM_{10} levels are those that exhibit the strongest and most significant reduction signal in both extremes and central tendency. From a regulatory point of view, trends in upper extremes are of higher interest than the general central tendency trends, as penalties that are imposed for breaches of the NES are based on the number of exceedences. This means a decrease in extreme values is needed to comply with national standards. As one exceedence per year is acceptable, upper percentiles are the crucial measure rather than maxima.

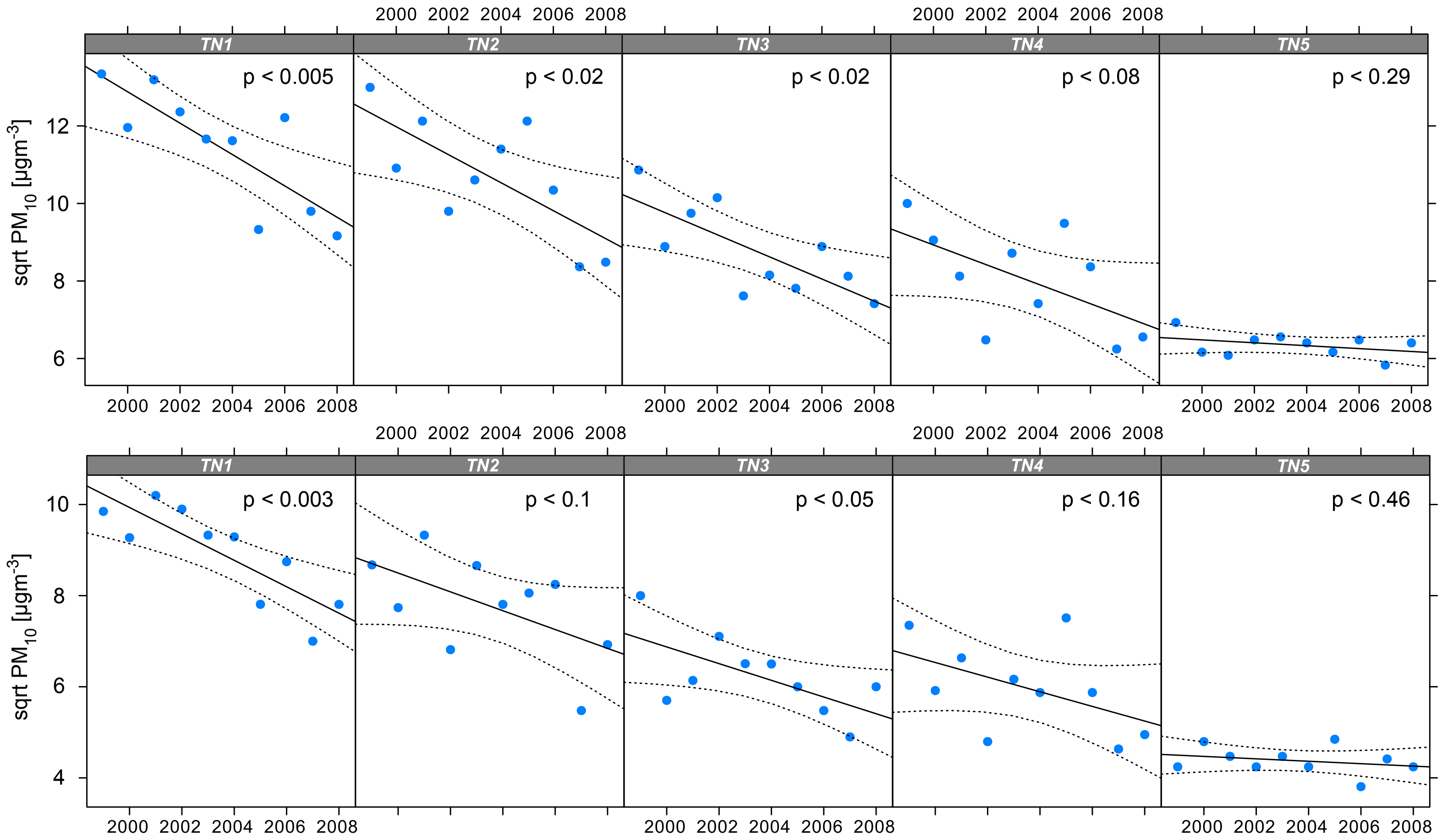

Figure 3.6: Trends of PM_{10} concentrations by TN between 1999 - 2008 for the 90^{th} percentile (upper panel) and median (lower panel). Regression line and 95% confidence interval are shown for each panel. Significance of slope is denoted as the p-level in top right corner of each panel.

3.3 Assessment of emission trends based on observations of PM_{10} concentrations

3.3.1 Introduction

This section is a modified version of the manuscript Appelhans et al. (n.d.). It outlines a statistical modelling approach to approximate emission strengths from observed concentrations of PM_{10} by identifying and subsequently removing the variance within these observations that can be accounted for by variations in meteorological conditions. Concentrations of ambient air pollutants are generally a result of two factors, the emissions and the dilution/dispersion potential of the atmosphere that these emissions are released into. This section presents a statistical approach to facilitate the identification of a trend in non-constant emissions derived from measured PM_{10} concentrations. Following the methodology presented by Wise & Comrie (2005*a*), multiple linear regression analysis is used to identify and remove meteorological influences on PM_{10} concentrations. This approach, however, assumes that emissions are approximately constant over time (e.g. from day to day) and that resulting concentrations are being modified mostly by weather conditions. As air pollution in Christchurch mainly stems from domestic fires operated during winter time, PM_{10} emissions cannot be considered constant over the course of a year due to the influence of temperature. Therefore, this dependency needs to be removed prior to the regression. Finally, a running mean filter is applied to extract the low frequency trend. This filter is based on the Kolmogorov-Zurbenko filter (KZ filter) which was first introduced to applications in ambient air quality investigations by Rao & Zurbenko (1994) to effectively separate different frequencies within a time series. Numerous studies have subsequently confirmed its usefulness in achieving various objectives within air quality research (e.g. Hogrefe et al. 2003; Ibarra-Berastegi et al. 2001; Porter et al. 2001; Yang & Miller 2002; Anh et al. 1997; Eskridge et al. 1997).

3.3.2 Methodology

3.3.2.1 Preparation of the time series

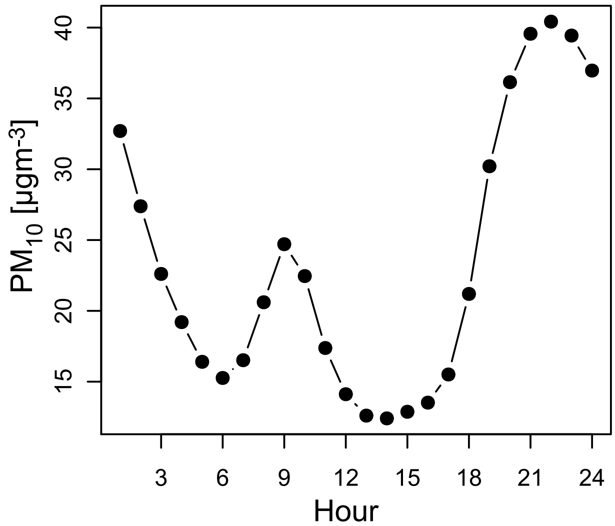

Figure 3.7: Average diurnal cycle of PM_{10} concentrations at Coles Place, St Albans between 1999 and 2006.

A time series of hourly averaged PM_{10} concentrations from the main air quality monitoring site located at Coles Place, St Albans was analysed in order to evaluate meteorological influences over the period 1999 - 2006 (inclusive). The time series of PM_{10} concentrations provided by Environment Canterbury is shown later in Figure 3.10 (upper panel) along with two other series which resulted from the statistical analysis outlined in Sections 3.3.2.2 and 3.3.2.3.

PM_{10}concentrations were averaged on a daily basis for the hours between 1700 hrs – 2400 hrs. Focus was given to evenings rather than daily averages for two reasons. First, daily averages are problematic when assessing atmospheric stability as positive lapse rates during the day and negative lapse rates during the night tend to cancel each other out so that meteorological influences become obscured. Second, it was found to be the main peak time for concentrations (Figure 3.7). Wind speed, 1 m air temperature and the vertical temperature difference between 1 m and 10 m, all obtained from the same site as the PM_{10} concentrations, were chosen to be representative of meteorological conditions. A comparison between observations from Ecan's air quality site and the automated weather station at Christchurch airport is given in Figure 3.8. Temperature recordings from both sites are very similar. There is little scatter and most observation pairs lie very close to the line

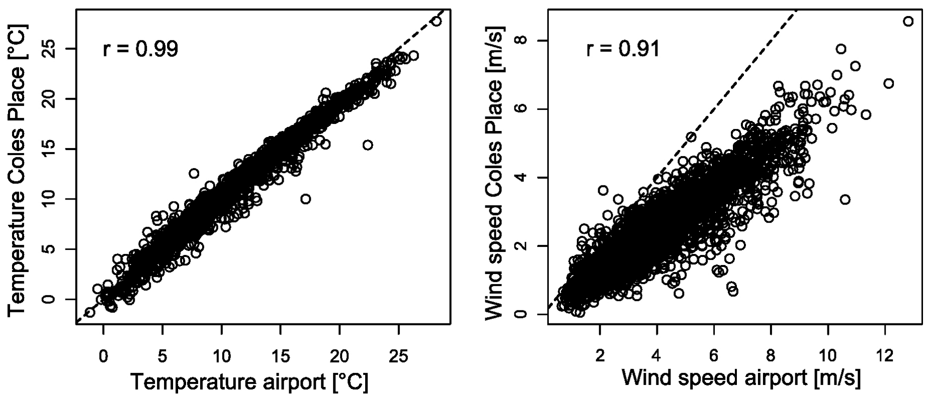

Figure 3.8: Comparison between observations recorded at Coles Place and Christchurch airport for temperature (left panel) and wind speed (right panel). Correlation coefficients are shown.

of equality (y=x) represented by the dashed line. The relationship between wind speed readings of the two sites exhibits higher scatter and shows that wind speeds are generally lower at Coles Place than at the airport. The increased scatter that is observed for wind speeds can be explained by the generally more variable nature of wind recordings. The higher wind speeds observed at the airport are testament to the fact that this site is situated outside of the city limits and is therefore much more exposed than the inner urban air quality monitoring site situated within an environment of enhanced surface roughness (both anemometers are installed at the same height above ground - 10 m). Wind speed and the vertical temperature difference between 1 and 10 m represent the intensity of horizontal and vertical mixing within the ABL, respectively. These meteorological variables were averaged over the 1700 hrs to 2400 hrs time period.

3.3.2.2 Approximation of constant emissions

The identified diurnal maximum of PM_{10} concentrations in the evening hours reflects the fact that by far the largest contribution to PM_{10} concentrations measured in Christchurch originates from home heating devices such as solid fuel burners. This makes emissions very variable as they are highly dependent on temperature variations and can therefore not be considered as constant over time (in comparison to emissions from traffic which show only little variation over the course of a year). In other words, ambient air temperature is a key cause of PM_{10} emissions in Christchurch, as thermal conditions influence the amount of fuel that is used for heating, whereas wind speed and temperature gradient difference modify concentrations via their effect on ventilation.

In line with Ott (1990) and Giavis et al. (2009), the distribution of PM_{10} concentrations was found to be log normal and therefore, values were transformed using the natural logarithm ($\log_e$), achieving a near-normal dataset (see Figure 3.9 – right panel histogram). Subsequently, the series was split into a winter and a summer season (April – September and October – March, respectively). Figure 3.9 shows the relationship between the logarithmically transformed PM_{10} observations ($\log_e$ PM) and temperature for both the summer (represented by dots) and winter (+) seasons. Clearly, no correlation between temperature and PM_{10} concentrations can be found during summer, whereas in winter a clear inverse dependency is observable. Therefore, wintertime observations were regressed against temperature and the calculated linear dependency was removed using the following formula, retaining the maximum variation by recalculating the observed residuals to represent deviations from a zero trend line (in this case the average of the mean concentrations in each season):

$$corr.log_{\mathrm{e}}PM = \cos(\arctan b) \cdot (log_{\mathrm{e}}PM - (a + b \cdot T)) + avg.log_{\mathrm{e}}PM$$

With $corr.log_e\ PM$ = natural logarithm of temperature-corrected PM_{10} concentrations, $log_e\ PM$ = natural logarithm of original PM_{10} concentrations, T = 1 m air temperature, $avg.log_e\ PM$ = mean natural logarithm of original PM_{10} concentrations for overall data (both seasons), a = intercept of the calculated regression and b = slope of the calculated regression.

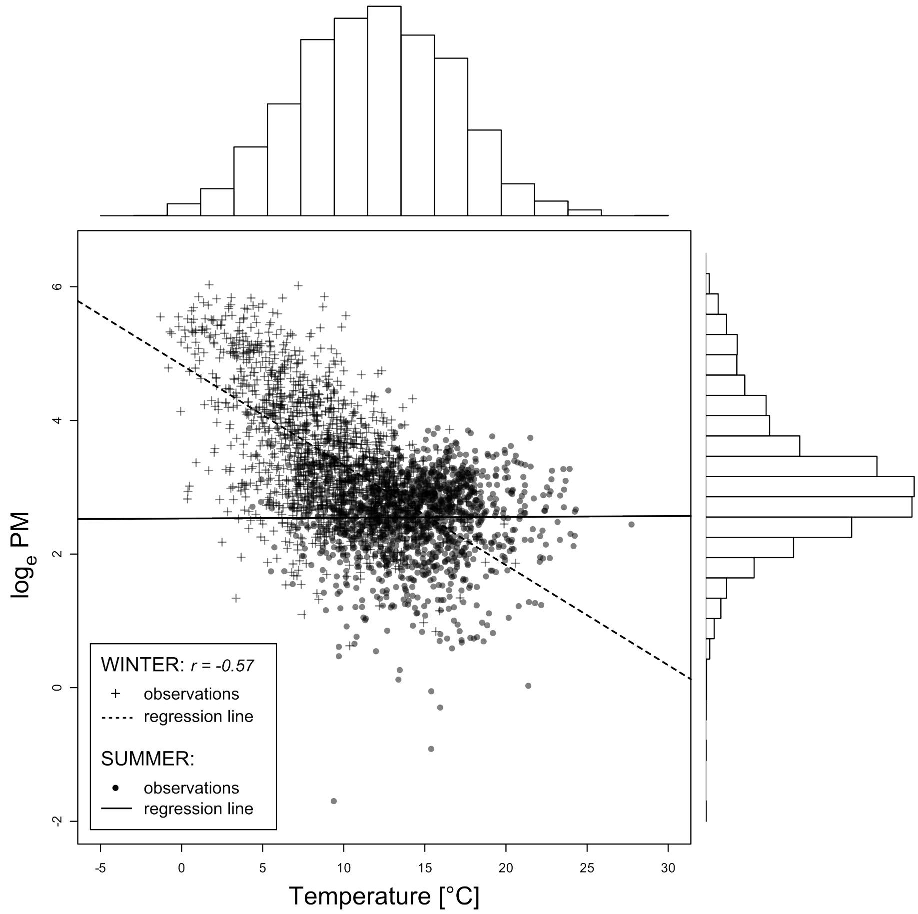

Figure 3.9: Correlation between $\log_e$ PM and temperature of the original time series for winter (crosses) and summer (dots). Histograms of the full record for temperature (top) and $\log_e$ PM (right) provide evidence for approximate normality of the data. For ease of visual inspection, dots and crosses are semi-transparent.

Summertime observations were scaled so that these recordings too are scattered around the overall mean rather than their seasonal average. The datasets were subsequently rejoined into one continuous time series, and this temperature corrected data set was then taken as the input time series for the multiple linear regression analysis to identify and subsequently remove remaining meteorological influences on PM_{10} concentrations in Christchurch.

3.3.2.3 Removal of meteorological influences

In order to remove the meteorological influences controlling horizontal and vertical mixing, multiple linear regression analysis was performed. The corrected logarithmic PM_{10} concentrations were selected as the dependent variable and regressed against the independent variables of wind speed (which was transformed using the square root to approximate a normal distribution; not shown) and temperature difference. No further significant relationships between atmospheric variables (including wind direction and relative humidity) and PM_{10} concentrations were found. The multiple regression was able to explain 20% of the remaining variance within the PM_{10} concentrations ($r^2 = 0.2$). To avoid mathematical problems associated with non-negativity of antilogarithms, it was decided to calculate residuals after antilogarithms of observed and predicted values were calculated to investigate the variation in concentrations that remained unexplained by the selected meteorological influences. The residuals reveal variations within PM_{10} concentrations due to factors other than meteorology and thus represent a better approximation of the behaviour of emissions (Wise & Comrie 2005*a*).

To make residuals comparable to concentrations they were added to the overall mean of the original (but temperature corrected) measurements. This step is necessary as residuals, by definition, only represent deviations from a calculated series of values – in this case the calculated series of optimal predictions of PM_{10} concentrations based on variations in wind speed and temperature difference – and therefore fluctuate around a zero line (i.e. their sum equals zero). This new dataset can now be understood as adjusted PM_{10} concentrations, where meteorological influences, namely 1 m air temperature, wind speed and presence and strength of a temperature inversion have been removed. Figure 3.10 shows both the temperature corrected (central panel) and the meteorologically adjusted time series (lower panel).

A simple moving average filter (based on the Kolmogorov-Zurbenko or KZ filter described in Rao & Zurbenko 1994) was applied to both the original and the adjusted PM_{10} data set. A window size of 365 days (evenings) was chosen to average out seasonal fluctuations and two repeated iterations were

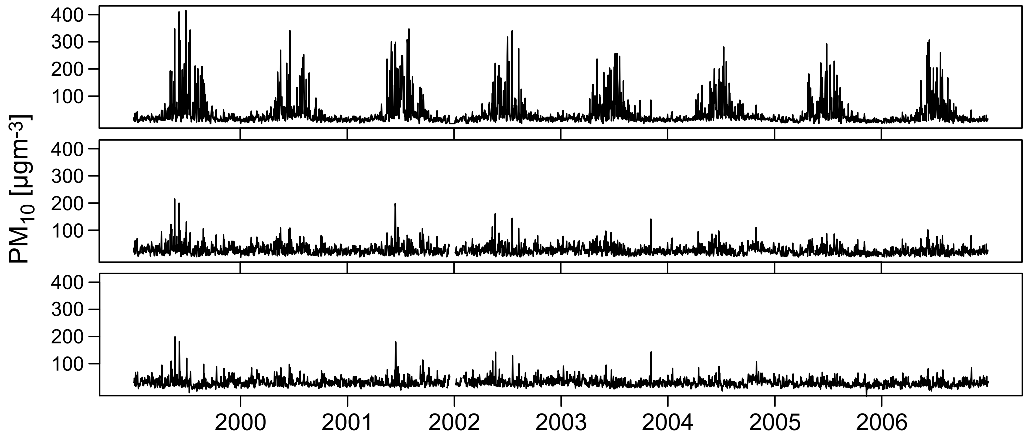

Figure 3.10: Time series plots of original concentrations (upper panel), temperature corrected observations (central panel) and meteorologically adjusted observations (lower panel).

run to facilitate interpretation of the trend. As the filter utilises a central moving average, each iteration truncates half the size of the chosen window length from each end of the time series, so that the first filter run effectively cuts one year off the time series and the second run two years (Wise & Comrie 2005*a*). A comparison of the resulting trends is shown in Figure 3.11. Only the trends obtained after the second iteration are shown. These lines are highly smoothed (removing fluctuations smaller than 1.4 years) to aid interpretation of the long term behaviour of PM_{10} concentrations. Rao & Zurbenko (1994) proposed the application of a third iteration to extract the low frequency trend. However, due to the short monitoring period and the outlined cut-off effect with each iteration, it was chosen to apply only two iterations in order to preserve a time span which allows a more robust interpretation of the extracted trend.

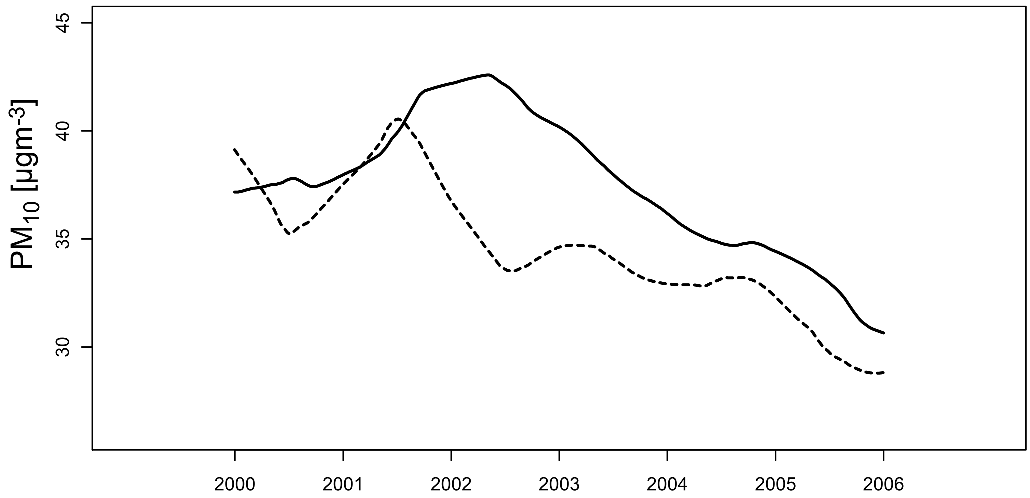

Figure 3.11: Trend comparison between original PM_{10} concentrations (dashed line) and meteorologically adjusted PM_{10} concentrations (solid line). Abscissa shows start of each year.

3.3.3 Results

The original trend for the evening hours (dashed line in Figure 3.11) follows the trend observed in daily averages (for comparison refer to **?**), reflecting general winter conditions which are primarily influenced by variations in mean temperatures throughout the winter months. This becomes particularly evident when comparing average concentrations for 2000 and 2001, reflecting respectively mild and cold winter conditions. The adjusted trend (solid line in Figure 3.11) suggests an increase in PM_{10} emissions with a peak in 2001/2002. Afterwards, emissions appear to decrease steadily. This differs somewhat from Environment Canterbury's emission inventories, which suggest a peak in emissions in 1999 and a steady decrease thereafter (Scott & Gunatilaka 2004). However, emission inventories are only carried out every three years which makes comparisons difficult.

3.4 Conclusion

This chapter has investigated how local meterological conditions govern air quality in Christchurch. It has shown that, on a local scale, varying degrees of air pollution potential can be identified that result from different low level flow characteristics and associated thermal conditions. Evidence is found that the various identified representations of local atmospheric conditions, are governed by processes that operate on larger spatial scales and that, in order to understand these processes, investigations have to be extended to mesoscale and synoptic scale anaylses. It is clearly evident that local scale relationships between meteorology and air quality can be established and help explain observed variability in a statistical exploratory manner. To understand underlying processes, however, the focus of investigation needs to be extended to meso- and synoptic scales, in which these processes originate. These larger scales of atmospheric motion are the subject of analysis in the following chapters.

Nonetheless, especially from a regulatory point of view, the findings presented here are of great value. Exceedence probabilities have been identified that provide a straightforward quantification of expected air quality as a result of atmospheric parameters. This is useful in terms of short-term air quality forecasting, as expected exceedence potential can be assigned to weather forecast scenarios. There was no evaluation of the accuracy of the identified exceedence probabilities given in this chapter, so that no conclusions about their prediction performance can be drawn at this stage. However, in a later chapter (Chapter 6), the results presented here will be used to lay the basis for an exceedence probability index in conjunction with synoptic conditions, and it will be shown that the identified pollution classes yield satisfactory prediction accuracies.

Most encouraging are the results of the trend analyses in this chapter. Two independent approaches found evidence for a decreasing trend in PM_{10} concentrations, independent of meteorological variability. This is of great value for local authorities, as it shows that their regulatory actions over the last few years appear to be enhancing air quality in Christchurch. In light of the findings by Scarrott et al. (2009), who also reported decreasing PM_{10} concentration trends for Christchurch, confidence in the results presented here is high and hence provides a solid positive evaluation of the effectiveness of the regulatory measures that have been implemented over recent years. In short, local policy regulations are showing the desired effect, although it is unclear whether the rate of improvement is sufficient to meet NES requirements.

Classification tree analysis as used in this chapter is an appealing method for exploring complex multivariate relationships for a wide range of applications. Graphical representation of the complex analysis in a decision tree provides easy interpretation of the results. Additionally, the classification is pure in the sense that each observation gets assigned to one terminal node and no overlaps occur. However, as mentioned in Section 3.2.2, classification trees are very sensitive to data input. This raises the question of reliability of the identified local exceedence potential classification. Thus, in order to gain a clearer understanding and to assess whether this classification could be enhanced with regard to class purity, it was decided to repeat the classification tree analysis described in Section 3.2.2 using a more comprehensive data set. Ecan routinely measures air temperature at two heights (1 m and 10 m above ground) at their air quality monitoring site in St Albans. Measurements of this vertical temperature gradient along with higher frequency temperature information (derived from hourly observations, similar to those for wind speed, as shown in Table 3.1) were introduced into the analysis. An in-depth description of the results of this modified classification tree analysis and how they compare to the classification presented in this chapter is given in Appendix A. In brief, following close inspection of the underlying statistics, it becomes obvious that the original analysis that uses the simpler set of predictor variables, provides a more reliable and robust classification. Furthermore, the incorporation of higher frequency measurements plus vertical temperature information did not yield a significant enhancement of the local exceedence probability classification with respect to class purity. In fact, identified probabilities for high pollution nodes are very similar and information on vertical temperature gradients exhibits less statistical power than general temperature and wind speed observations. This confirms the findings of Owens & Tapper (1977), who used mixing depth as a measure of stability and did not find significant correlations with concentrations of several pollutants, including smoke. They found, however, temperature and wind speed to be significantly correlated with pollutant concentrations. The relationship between atmospheric stability and pollution dispersion, in particular the dispersion of particulate matter, is well established in the international literature and has been reported in innumerable scholarly publications (e.g. Sanchez et al. 1990, Glen et al. 1996, Wise & Comrie 2005*b*), and in more general texts such as Oke (1987) and Zawar-Reza & Spronken-Smith (2005). Jacobson (1999) evaluated soil moisture effects on pollutant concentrations via their effect on low level atmospheric stability. In the light of this, it is rather surprising to find that low level atmospheric stability does not seem to exhibit the expected effect on pollution concentrations in Christchurch (or is at least of lower importance than influences of temperature and wind speed). One characteristic that was found in this chapter, points towards a possible explanation. The fact, that high pollution classes, namely TNs 1 and 2, were found to be associated with a clear diurnally reversing wind regime, in conjunction with the fact that the evening transition between the two flows seems to happen earlier in TN1 than in TN2, indicates that this transition, and moreover the timing of it, is crucial with regard to PM_{10} dispersion. If this is the case, then it can be assumed that the earlier occurrence of the transition in TN1 exacerbates the build up of pollutants, as reflected by the higher amount of exceedences and the generally higher concentrations found under these conditions. At the same time, transitions between two flow directions generally indicate the clash of two air masses, which can also be associated with slightly enhanced mixing, and hence decreased stability. The observed night-time cooling under north-easterly flow in TN2, which is significantly smaller in TN1, supports this argument. It indicates that when the flow transition does not occur, nocturnal stability may be enhanced, yet PM_{10} concentrations are lower and less exceedences are observed. This is also in line with the observations of Owens & Tapper (1977), who found no clear relationship between low level stability and smoke concentrations. The following chapter will investigate this issue further by analysing meteorological conditions described by TN1 and TN2 with associated PM_{10} concentrations in more detail. Furthermore, greater emphasis will be given to the role of the identified transition meteorology.

Chapter 4

Surface wind regimes and associated PM_{10} dispersion

4.1 Introduction

Building on the findings in Section 3.2.3, this chapter examines the processes that govern local meteorology and associated pollution levels when conditions are most conducive to elevated PM_{10} concentrations. In general, low level air flow over Christchurch when air quality deteriorates results from complex interaction of local to regional scale features. Kossmann & Sturman (2004) and Corsmeier et al. (2006) found that, provided synoptic flow is weak, cold air drainage from the Port Hills and katabatic winds from the foothills of the Southern Alps converge over the city causing a stagnation zone with very low wind speeds. Clear skies and undercutting of cold drainage flow promote very stable conditions in the lowest 50 m above the surface (Corsmeier et al. 2006, McKendry et al. 2004). A third component which influences low level flow over Christchurch is the Canterbury North-Easter, as described in McKendry et al. (1987). In Section 3.2.2, it was shown that frequency and, perhaps more importantly, timing of the transition between day-time north-easterly winds and night-time westerlies to north-westerlies is influential when assessing exceedence probability on a daily basis (see Figure 3.2). It is indicated that in the class with highest pollution potential (TN1), this transition happens earlier than under meteorological conditions described by TN2. This chapter examines the differences in meteorological conditions between terminal nodes one and two in more detail. Variation in hourly PM_{10} concentrations as a result of varying meteorology are examined. Furthermore, in order to assess the role of possibly varying emissions that may contribute to the observed differences in concentrations, a numerical modelling study is carried out, that assimilates climatological wind field data that is based on the findings made in Section 3.2.3. The aim is to see how the flow reversal between day and night influences spatial distribution, duration and intensity of the evening peak in PM_{10} concentrations over the city. If local authorities are to successfully implement management strategies, it is necessary to understand how dispersion is likely to be modified according to dominant flow regimes.

4.2 Nocturnal flow regimes and their influence on PM_{10} concentrations

In Section 3.2.3 local meteorology was analysed with regard to the classes identified in Section 3.2.2. Meteorological parameters that were investigated were collected at Christchurch airport, as the classification tree analysis used these to facilitate the identification of meteorological proxies that will later be used to assess historic air quality potential in Christchurch. In this section, analysis of local meteorology and its influence on PM_{10} concentrations is extended using meteorological data collected at the air quality measurement site at Coles Place. Furthermore, in Section 3.2.3 information on air quality was restricted to the frequency distribution of the binary evaluation as to whether the national guideline was exceeded or not on a given day. Here, pollution levels will be investigated in greater detail using hourly concentration measurements.

A look at the diurnal variation of PM_{10} concentrations within each of the terminal nodes in Figure 4.1 reveals that the greatest differences are related to the rate of increase in concentrations in the evening. The difference between TN1 and TN2 is especially pronounced, as a result of the lower wind speeds

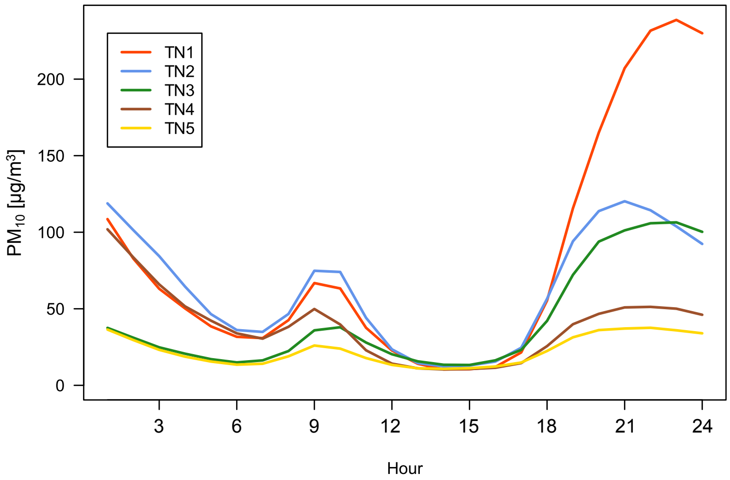

Figure 4.1: Average diurnal PM_{10} concentrations at Coles Place by TN.

after 1800 hrs. Apart from the difference in magnitude, a notable delay of peak concentrations of about two hours is apparent in TN1 when compared to TN2. Even though evening concentrations for TN3 are similar in magnitude to those for TN2, the analysis that follows is concentrated on the conditions that lead to PM_{10} concentrations as observed in TNs 1 and 2, as these clearly account for the majority of exceedences that occur in Christchurch.

Figure 4.2 shows the general meteorology that is described by TN1 and TN2 at Coles Place similar to Figure 3.2 (smoothing parameters are identical). Additionally, the low level temperature gradient between 1 m above ground and 10 m above ground (expressed as the difference 1 m minus 10 m - hence lower values indicate increased stability) is shown to get an indication of low level stability. The general flow pattern is similar to that seen at the airport, with TN2 being more dominated by day-time north-easterlies. Furthermore, increased day-time wind speeds associated with southerly to south-westerly and north-easterly wind directions are in line with the previous observations. Also in agreement with the conditions at the airport is the more dominant diurnal flow reversal signal in TN1. The relatively higher day-time wind speeds associated with conditions described by TN1, however, are in contrast to the conditions at the airport. Day-time south-westerlies show enhanced frequencies at the expense of southerlies, especially in TN1.

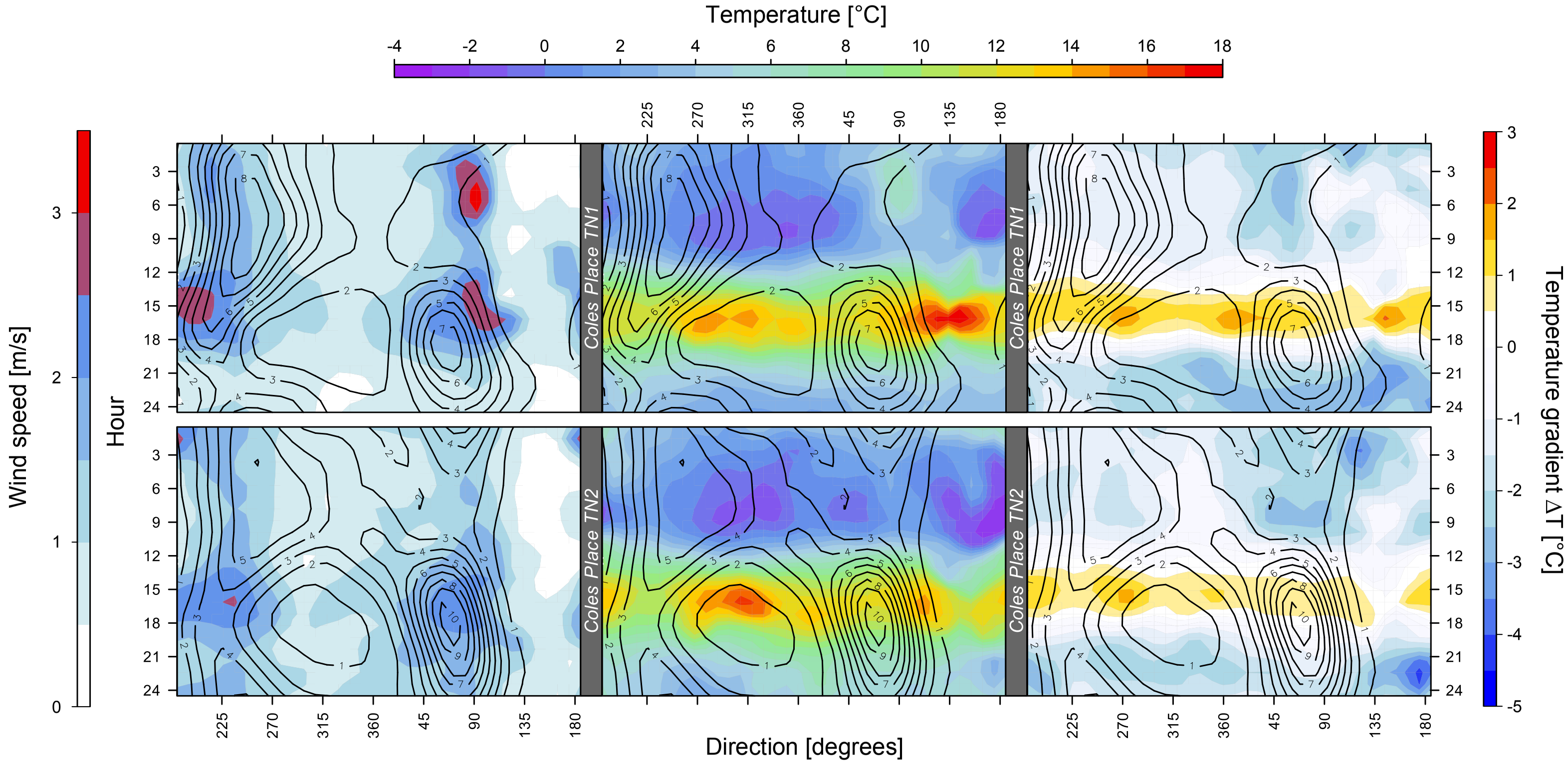

Figure 4.2: Contour plots of hourly wind direction frequency in percent (contour lines) for TN1 (upper panel - see inter-panel strips for labelling) and TN2 (lower panel) at Coles Place for the months May - August, 1999 - 2008. Colour contour shading shows average hourly wind speeds (left panels), average hourly air temperatures at 1 m above ground (central panels) and average hourly air temperature gradient (1 m above ground minus 10 m above ground - right panels) with regard to wind direction. Number of days that these plots are based on is 108 & 105 for TN1 and TN2, respectively (see Figure 3.1).

Additionally, nocturnal flow directions at Coles Place are generally shifted slightly towards the south-west. This may simply be an effect of the local urban environment, so that it depicts the influence of air channelling along street canyons. It may, however, also be a function of the geographic location of the station (to the south-east of Christchurch airport - refer to Figure 4.8 in Section 4.3 for a map of station locations) in relation to the flow splitting around Banks Peninsula. More importantly, the transition between day-time flow and nocturnal flow is delayed, most likely due to the fact that the slow moving alpine drainage winds have to cover a greater distance and will therefore generally arrive later at Coles Place. With regard to thermal conditions, the two terminal nodes do not reveal a great deal of difference, apart from the fact that evenings in TN1 are generally slightly colder. In both cases, nocturnal cooling is highest under northerly to north-westerly flow, with TN2 again showing cooler temperatures in the early morning. Nocturnal stability, however, as indicated by ΔT, seems to be highest under north-easterly flow in both cases. Unfortunately, the temperature gradient between 1 m and 10 m above ground measured in a residential built-up environment is not a great indicator of atmospheric stability. Potential shading effects of surrounding buildings/trees and modified low level turbulence - both enhanced turbulence as a result of measurements being made within the roughness layer as well as potential downstream wake effects with decreased turbulence in certain situations - are expected to have a huge impact on the representativeness of the actual atmospheric layering. However, these measurements are the only available observations that are routinely collected at a satisfactory frequency. Atmospheric soundings not carried out in Christchurch. Thus, it is crucial to bare in mind that interpretations relating to atmospheric stability and its potential implications can only be made with limited confidence. Nonetheless, it would be unwise to completely ignore or neglect potential information that may be provided by these measurements.

Figure 4.3 shows average hourly PM_{10} concentrations with regard to wind direction (left panels). Again, the figure is similar to Figures 3.2 and 4.2 with identical smoothing parameters. This time, however, the y-axis has been shifted by 12 hours so that it is centered around midnight, to enable

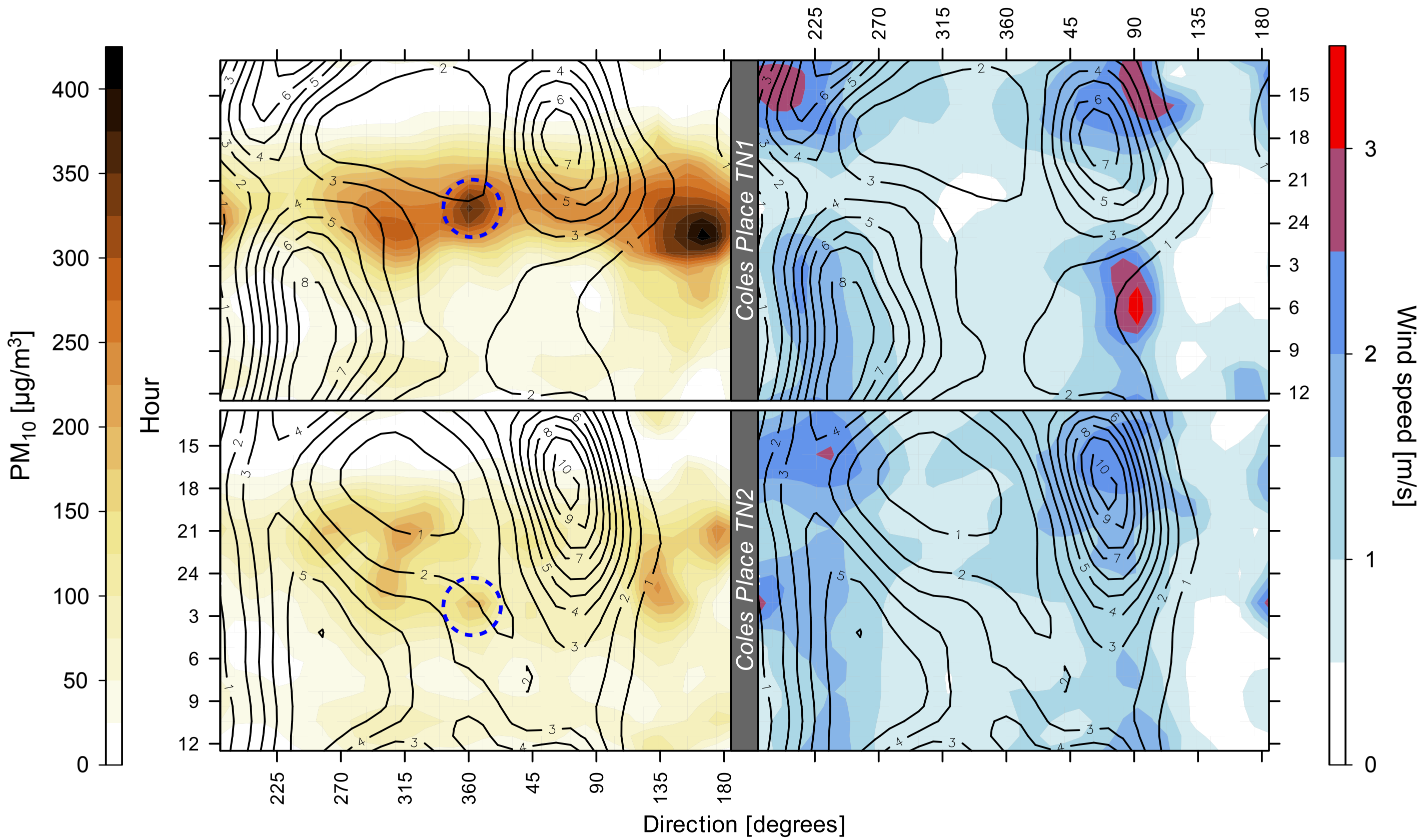

Figure 4.3: Contour plots of hourly wind direction frequency in percent (contour lines) for TN1 (upper panel - see central strip for labelling) and TN2 (lower panel) at Coles Place for the months May - August, 1999 - 2008. Colour contour shading shows average hourly PM_{10} concentrations (left panels) and average hourly wind speeds (right panels) in relation to wind direction. Dashed blue circles highlight increased PM_{10} concentrations during flow transition. The number of days that these plots are based on is 108 and 105 for TN1 and TN2, respectively (see Figure 3.1).

interpretation focussed on the time of day that exhibits highest PM_{10} concentrations and relevant meteorological processes. Average hourly wind speeds are also shown (right panels) for ease of interpretation. As mentioned in Section 3.2.3, conditions under south-easterly flow cannot be considered to be representative of general conditions, as much of the colour shading is an effect of the smoothing over data gaps due to the low frequency of occurrence. Therefore, south-easterly conditions will not be analysed here, even though they yield some of the highest hourly concentrations in both cases.

It is to be expected that absolute concentrations mirror the exceedence based classification, thus is it not surprising to see PM_{10} at higher levels when comparing TN1 to TN2. Also, as a result of the classification (lower wind speeds), a very prominent increase in PM_{10} concentrations after 1800 hrs is evident in TN1. This signal is more or less independent of flow direction, with the exception of south-westerly winds, which exhibit less potential to degrade air quality. A look at Figure 4.2 reveals that south-westerly flow tends to be windier, and thus associated with enhanced turbulent mixing which in turn decreases nocturnal heat loss at the surface. This is observed in both classes. Flow directions that cause highest concentrations are clearly from northerly to westerly quadrants, while north-easterlies tend to be associated with (in the case of TN1 only slightly) lower particulate levels, especially in TN2. This again highlights the increased influence of this regime in conditions described by TN2. In TN2, highest concentrations are associated with flow from north-westerly directions, with a distinct short maximum around 2100 hrs. Maximum emission release in Christchurch is estimated to occur a few hours prior to this at around 1900 hrs (Zawar-Reza & Sturman 2008; refer to bottom panel in Figure 4.10 in Section 4.3). TN1 on the other hand, paints a very different picture of maximum concentrations than TN2. Under north-westerly flow, the peak is delayed and occurs around or slightly after midnight. It is, however, indicated that even higher concentrations can be observed slightly earlier in a short but intense peak, when flow comes from the north (indicated by the dashed blue circle in Figure 4.3). Timing (approximately 2300 hrs) and location (northerly flow direction) of this peak indicates that this maximum is likely to be a direct result of the transition between day-time north-easterly flow to night-time westerlies. Fernando (2010) reported a particulate matter increase of up to ten fold within tens of minutes of the arrival of fronts between two air masses. The same signal of a short peak under northerly flow is apparent in TN2 about 3 hours later at approximately 0200 hrs, although, much alleviated. Nonetheless, it is indicating the same process of flow transition and associated elevated levels of particulates.

Figures 4.4 and 4.5 show meteorological parameters along with PM_{10} observations at Coles Place between 1200 hrs and 0600 hrs on a case by case basis for TN1 and TN2, respectively. These cases represent events when two consecutive days are assigned to the same class, i.e. TN1 $\rightarrow$ TN1 or TN2 $\rightarrow$ TN2, and a change from day-time north-easterly flow to nocturnal westerly flow is apparent. Each panel represents a single event. Parameters shown in these figures are wind direction WD (red diamonds), wind speed WS (dashed green lines), low level temperature gradient ΔT between 1 m and 10 m above ground (solid blue lines) and PM_{10} concentrations (dotted brown lines). White areas denote flow before the transition, whereas grey areas show flow after the transition. Cases A1 and F1 in Figure 4.4 do not show a clear diurnal signal with regard to flow direction, hence no shading is given. All cases in both figures show increasing low level stability (i.e. ΔT becomes more negative) after about 1500 hrs to 1700 hrs. This increase, in most cases, is accompanied by a decrease in wind speed. As flow intensity drops and stability increases, PM_{10} concentrations rise as a result of decreased dispersion in a calming low level atmospheric layer. Times of lowest wind speeds are usually when the transition between the two surface wind modes occurs. After this, in almost every case, low level stability seems to steadily decrease, even though there is not much increase in flow intensity (apart from a few cases, such as B1 in Figure 4.4, where wind speed and stability closely follow the same trend). As mentioned before, the stability parameter that is employed here is not ideal and the observed decrease during the night might simply be an effect of poor siting of the instruments. It is, however, peculiar how well the timing of the flow transition matches the time when low level stability starts to abate.

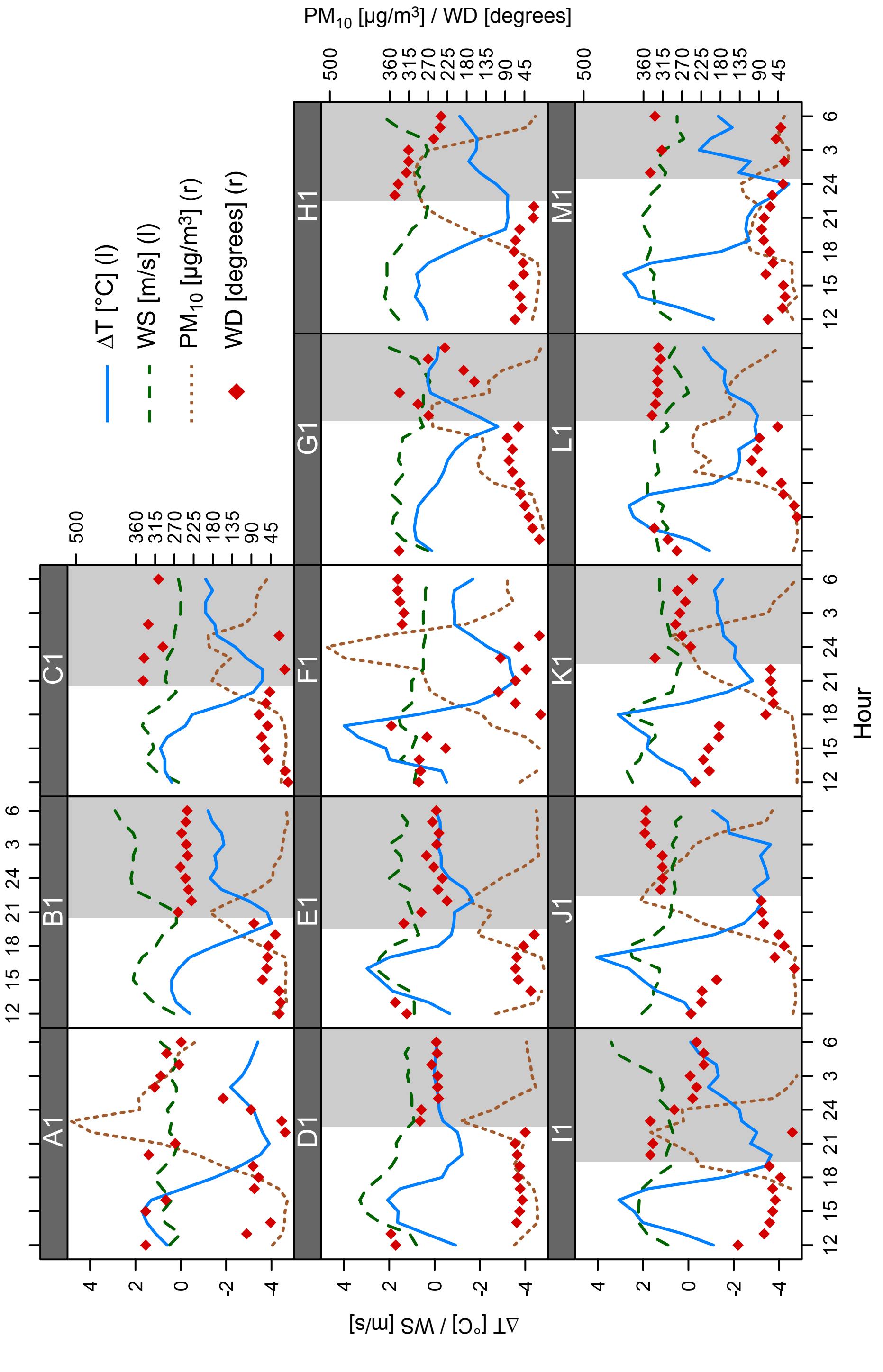

Figure 4.4: Time series plots of low level temperature gradient ΔT (solid blue line), wind speed WS (dashed green line), PM_{10} concentrations (dotted brown line) and wind direction WD (red diamonds) for selected cases of TN1 between 1200 hrs and 0600 hrs. Shading denotes time before (white) and after (grey) transition.

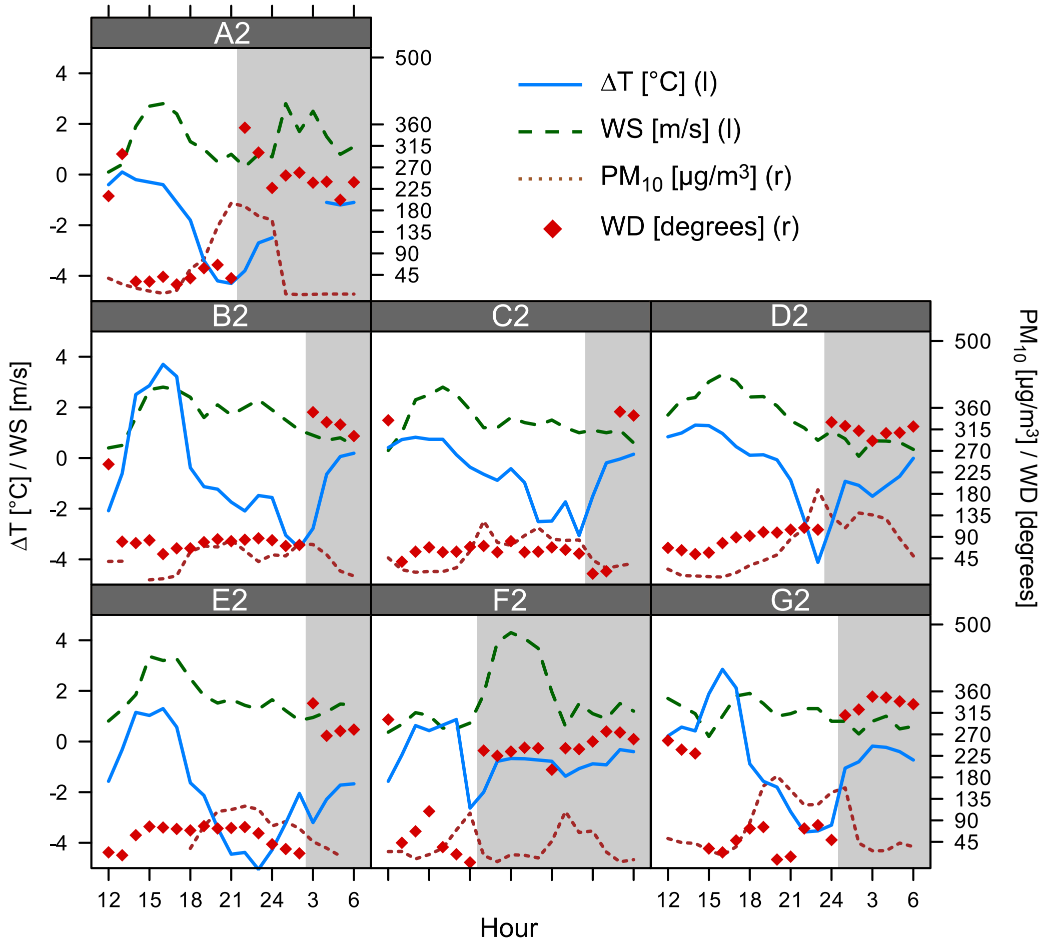

Figure 4.5: Same as Figure 4.4, but for selected cases of TN2.

Recently, Fernando (2010) published a comprehensive review of findings that were published in the last decade or so in the field of fluid dynamics of urban atmospheres that are located in, or influenced by, complex terrain. With reference to Hunt et al. (2003) and Brazel et al. (2005) he presents a summary of how frontal features can develop on slopes resulting from the interaction (transition) of anabatic and katabatic winds. These frontal features are generally associated with low wind speeds and subsequent enhanced turbulent mixing, both a result of the interaction of two air masses with different physical characteristics. He furthermore states that such fronts can also develop as a result of the interaction between local air masses and katabatic density currents, that were formed elsewhere. In the case of Christchurch, this is rather important as, as has been shown by McKendry et al. (2004), Corsmeier et al. (2006) and Kossmann & Sturman (2004), katabatic drainage winds from the Southern Alps and the Port Hills play a major role with regard to air pollution climatology. Apart from flow stagnation as a result of opposing low level flow, these studies attribute part of the mechanism that promotes elevated smog levels to increased low level stability as a result of the undercutting by slow moving cold air. Whereas the flow stagnation is found in this investigation also, there is no sign of increased low level stability as a result of the advection of cold alpine air masses. On the contrary, observations presented in this section indicate decreasing thermal stability after the arrival of the density current front, at least very close to the surface (in the lowest 10 m). Increased pollution levels are thus merely a result of flow stagnation and recirculation due to the interaction of two air masses with opposing flow directions.

The following sections outline mesoscale numerical model experiments forced with climatological averages from several stations, that was carried out to further investigate the mechanisms that lead to higher PM_{10} concentrations as observed under meteorological conditions described by TN1 when compared to TN2.

4.3 Modelling surface flow regimes and associated pollution dispersion mechanisms

So far, analysis of meteorological and air quality point observations has indicated that the occurrence and, more importantly, the timing of local flow transition between day-time north-easterlies and night-time westerlies plays a crucial role in controlling ambient levels of particulates in Christchurch. Hence, with a generally earlier occurrence of this transition, PM_{10} concentrations are increased in TN1. However, until now, all analyses have neglected the influence of possibly varying emissions when assessing different dispersion mechanism scenarios.

In order to gain confidence in the postulated dispersion mechanism controlled by flow transition meteorology, idealised case simulations with fixed (though hourly varying) emissions were carried out. The Air Pollution Model TAPM (V4; Hurley 2008) was used in a novel way to determine the effects of the different flow regimes described by TN1 and TN2 in controlling temporal and spatial concentration patterns of PM_{10}.

TAPM is a three-dimensional incompressible, non-hydrostatic, primitive equations model, which uses a terrain-following coordinate system. The model includes gas-phase photochemical reactions, as well as wet and dry deposition effects on suspended particulates (e.g. $PM_{2.5}$ and PM_{10}). In this study, the tracer mode of TAPM is used to simulate PM_{10} dispersion. In addition, the tracer extinction coefficient is set to zero, indicating negligible mass loss due to adsorption to the surface and chemical transformations. This setting has been used in previous studies (e.g. Zawar-Reza & Sturman 2008). TAPM has previously been used in Christchurch to assess long-term exposure to PM_{10} (Wilson & Zawar-Reza 2006), and its performance has been compared to more sophisticated models (Zawar-Reza et al. 2005). Since the focus is on local low level flow processes, it was chosen to ignore the effects of synoptic scale variation. Therefore, user-defined 3-dimensional fields for the entire depth of the model domain were prepared that contain no large scale wind information (i.e. the atmosphere is assumed to be at rest) and, in addition, vertical profiles for temperature and humidity were set according to the standard atmosphere and were kept constant throughout the simulations, while the boundary condition were set to zero gradient. Figure 4.6 shows the vertical potential temperature profile that was used to initiate the simulations. Such a technique is common in numerical studies and is referred to as horizontally homogeneous initialization. To study the effect of basin geometries on local wind systems, De Wekker et al. (1998) used a similar initialization procedure. With homogeneous initialization, as the simulation progresses, mesoscale temperature perturbations are introduced by the heating/cooling cycle of the surface, leading to horizontal pressure gradients that drive local circulations such as sea-breezes (in the absence any large-scale or synoptic scale perturbation).

Note that horizontally homogeneous initialization does not affect the formation and destruction of the nocturnal inversion layer or the formation of the daytime superadiabatic layer. The boundary layer profiles are allowed to develop freely in response to surface heating/cooling. Simulations presented here use four domains with grid spacing of 15, 5, 2 and 0.8 km respectively. This setup provides adequate resolution of the local topography. Each domain has 50 zonal and meridional grid nodes with 30 vertical levels stacked on top to provide high resolution in the vertical axis also. The first two vertical levels are at 10 and 25 m, respectively, while the highest model level is near 8000 m. To better resolve boundary layer processes, the lower portion of the domain has higher vertical resolution. This vertical resolution decreases linearly with height.

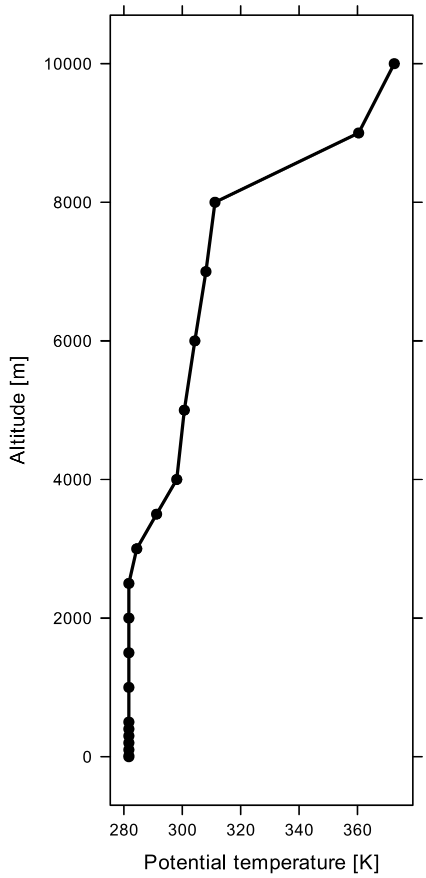

Figure 4.6: Vertical profile of potential temperature used at initiation time for the simulations.

Once the local scale winds are generated by TAPM using the initialization procedure described above, the simulated wind fields can be improved (i.e. nudged closer to observational data) by data assimilation. In this analysis, the assimilation option available in TAPM is driven by climatological averages of low level flow derived from the classification tree analysis described in Section 3.2.2. Neglecting synoptic forcing provides the ability to investigate fundamental modes of local scale flow operation without modification of day-to-day weather variability. In other words, an autonomous atmospheric environment is created where flow over the area of emission release is controlled, thus providing a highly idealised atmospheric setting to assess general dispersion behaviour over Christchurch in response to dominant modes of mesoscale low level flow.

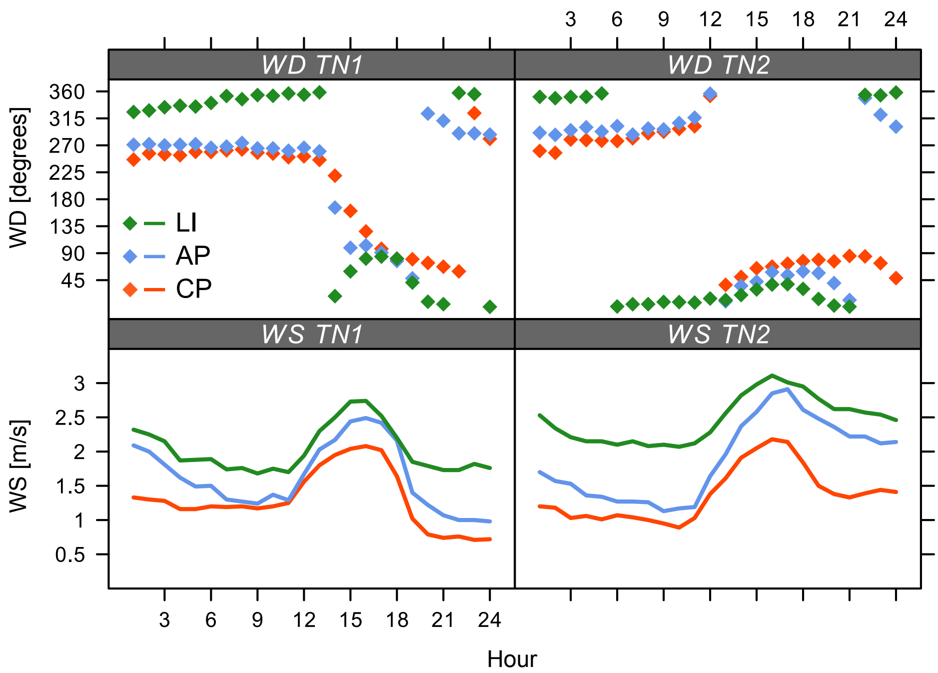

Figure 4.7: Idealised observations of wind direction WD (top panels) and wind speed WS (bottom panels) for data assimilation at Lincoln (LI - green), Christchurch airport (AP - blue) and Coles Place (CP - red). A description on how these were obtained is given in the text.

4.3.1 Data assimilation

Two 1-day simulations were conducted, one based on the meteorology as described by TN1, the other for TN2. Wind speed and direction data for all days that were classified as TN1 (TN2) were averaged for each hour of the day so that idealised diurnal wind measurements were artificially created (Figure 4.7). These climatological low level wind field averages were created and assimilated into the model for 3 stations in and around Christchurch at Coles Place (CP), Christchurch Airport (AP) and Lincoln (LI). A map of their location is shown in Figure 4.8.

In these idealised scenarios, nocturnal flow at Coles Place and Christchurch airport is generally from the west. During the afternoon, flow is dominated by north-easterlies, before it switches back to north-westerly and westerly flow directions during the evening. At the airport, this transition occurs three hours earlier than at Coles Place. As a result of this, evening flow at Coles

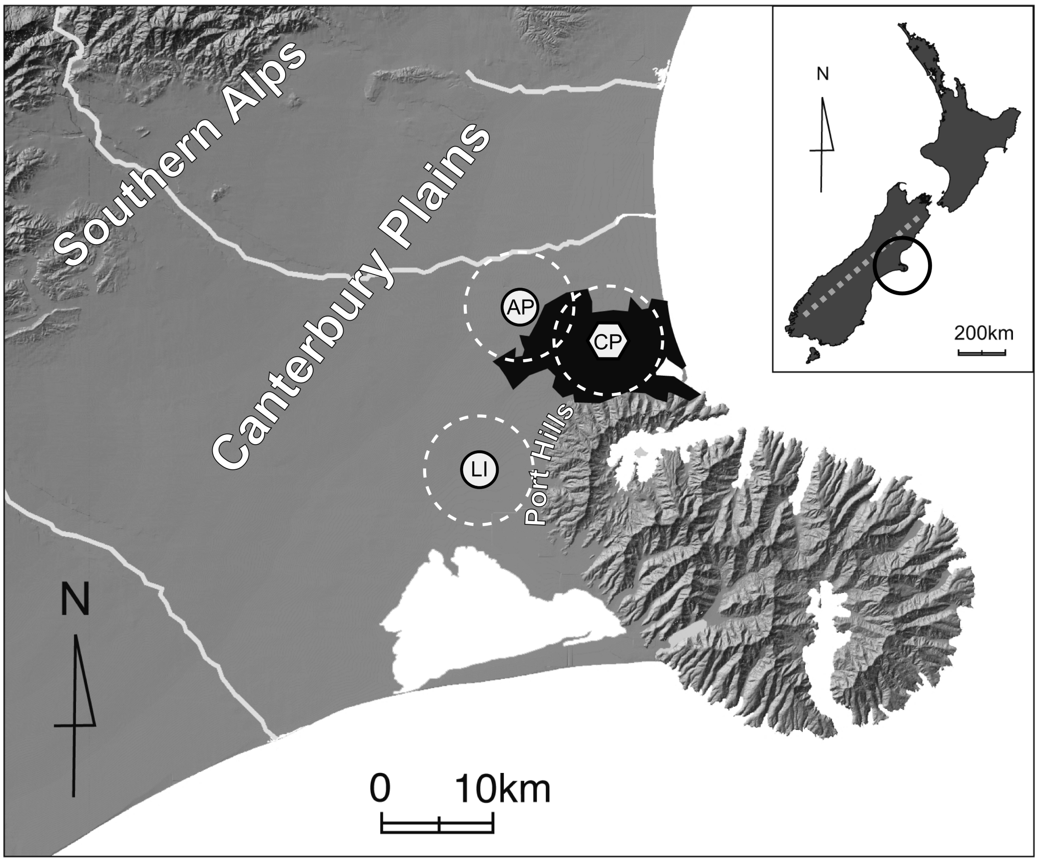

Figure 4.8: Map of the northern Canterbury region showing location of stations utilised for data assimilation. Black circles show wind measurement sites at Christchurch airport (AP) and Lincoln (LI), the black hexagon shows the station at Coles Place (CP) that also records air quality. Dashed white circles indicate approximate horizontal region of influence for assimilated wind field climatologies. The dashed line in the inset indicates the approximate location of the Southern Alps.

Place stays north-easterly in the case of TN2, as the transition is delayed and happens after midnight. At Lincoln, flow is mostly northerly with a general tendency towards north-easterlies during the afternoon (with TN1 showing an enhanced diurnal signal). Wind speeds are generally highest at Lincoln and lowest at Coles Place, with a distinct day-time maximum as a result of increased thermal forcing. Flow intensity decreases in the evening, but, as a result of the classification that underlies these idealised measurements, this calming is enhanced in TN1. Northerly dominated flow at Lincoln (especially at night-time) indicates flow convergence and subsequent speed-up of either katabatic winds from the Alps and drainage winds from the Port Hills, or the convergence of katabatic alpine winds and the north-easterly. In general, the artificially created idealised climatological wind field observations can be considered to provide a good representation of the differing meteorological conditions described by TN1 and TN2.

Assimilation data for each of the 3 sites was set to have a horizontal radius of influence of 5000 m (indicated by the dashed white circles in Figure 4.8) and a vertical influence of 4 grid levels (i.e. the lowest 75 m of the atmosphere). As climatological averages were created from more than 100 days in each case, reliability of the assimilated data was assumed to be high and the data reliability indicator in TAPM was set to 1 accordingly.

4.3.2 Emissions

Emission release was simulated using an area source based on a time-varying emission profile of hourly estimates provided by Environment Canterbury (Scott & Gunatilaka 2004 - refer to bottom panel in Figure 4.10). The same profile was used for both simulations, so that differences in concentrations can be attributed to the varying low level meteorology between the two cases, rather than variations in emission release. With regard to the investigation of spatial variation that stems from differences in low level flow rather than emission release, it was chosen to use a uniform area emission source. In contrast to gridded emission sources, which, in addition to the temporal dimension, also provide spatial variation of emissions, area source files release a uniform amount of particulates into the model domain across the specified area at each time step of the simulation. Furthermore, in a previous study for Invercargill, Wilton et al. (2009) found that differences in simulated PM_{10} concentrations between these two source types were small (see circles and crosses in Figure 4.9).

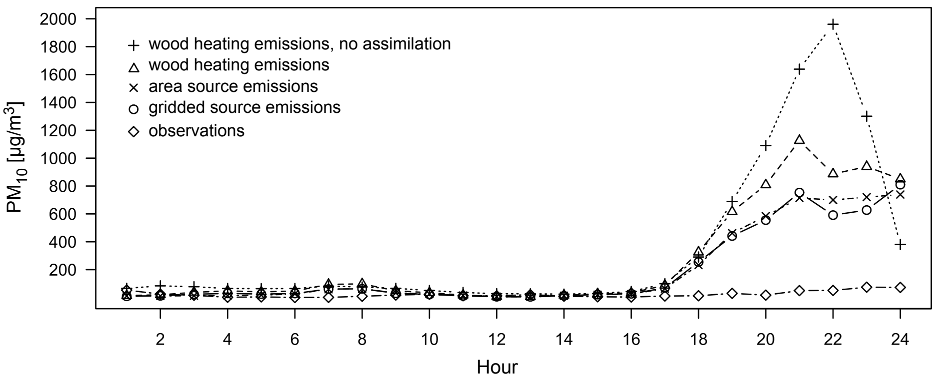

Figure 4.9: Comparison of simulated PM_{10} concentrations for Invercargill in response to different emission source types (from Wilton et al. 2009). For further information and definitions of emission source type configuration, refer to Hurley (2008).

4.3.3 Results

Analysis of the modelling results in this section is restricted to the second part of the day (1200 hrs - 2400 hrs) for a number of reasons. As described in Pielke (2002), numerical mesoscale models need a certain start-up time to adjust the initial conditions to the local forcings, so that numerical modelling studies generally allow the model to 'spin-up'. In the simulations presented here, a spin-up time of twelve hours was deemed appropriate, so that analysis is restricted to the second part of the day. Predictions in the early stages of the simulations over-estimate PM_{10} concentrations, but by midday observations and predictions show good agreement. Simulated and observed PM_{10} concentrations for both simulations between 1200 hrs and 2400 hrs, along with the hourly varying emission release profile, are shown in Figure 4.10 (top panel and bottom panel, respectively). It becomes obvious that the simulations reflect the differences in both relative magnitude and timing of the evening peak between the two cases very well. Modelled concentrations for TN1 are significantly higher and the time of maximum modelled concentrations during the evening is delayed. The sharp decrease in modelled concentrations after the peak is not seen in the idealised observations. However, in this case, observations are climatological averages and therefore highly smoothed. Refer to Figures 4.4 and 4.5 to see that abrupt decay of

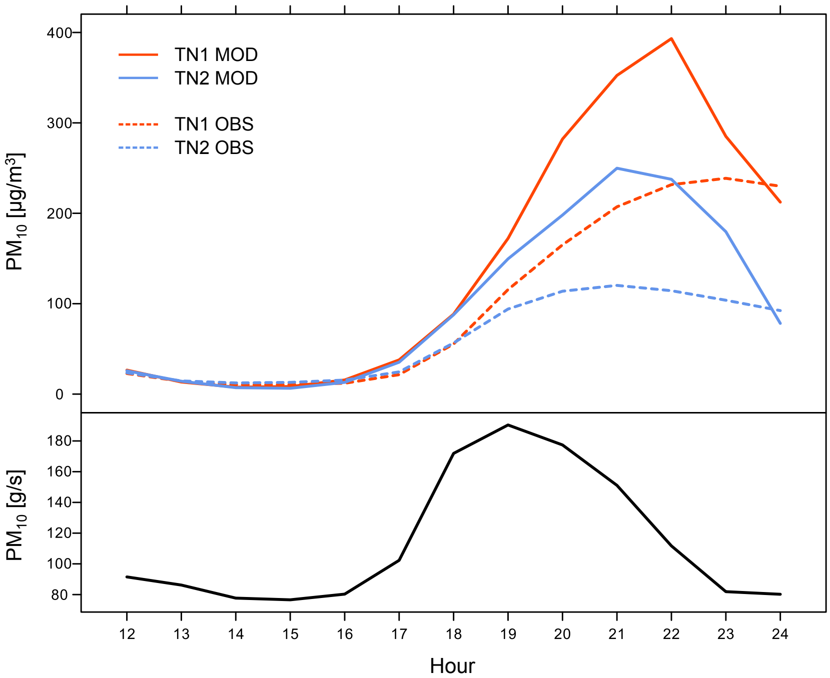

Figure 4.10: Comparison between modelled (MOD - solid lines) and observed (OBS - dashed lines) hourly PM_{10} concentrations at Coles Place for TN1 (red) and TN2 (blue) between 1200 hrs and 2400 hrs. Bottom panel shows respective hourly emission release in grams per second used in both simulations.

particulate matter concentration is regularly observed on individual nights. The fact, that the absolute magnitude of concentrations is over-estimated, might well be a function of the amount of emissions that are released into the model domain. This may indicate that Ecan's estimated emission profile is assuming unrealistically high emissions. Furthermore, the temporal signal of emission release may also be misrepresented by the profile, as indicated by the premature increase in simulated concentrations after 1600 hrs. However, it is encouraging to see how well the two most crucial features in pollution build-up are depicted by the model. Given that emission release in the two simulations is identical, the observed differences in resulting PM_{10} concentrations must be a result of different atmospheric dispersion mechanisms. Thus, these simulations provide means to investigate the proposed mechanism of flow stagnation and recirculation as a result of the transition between two

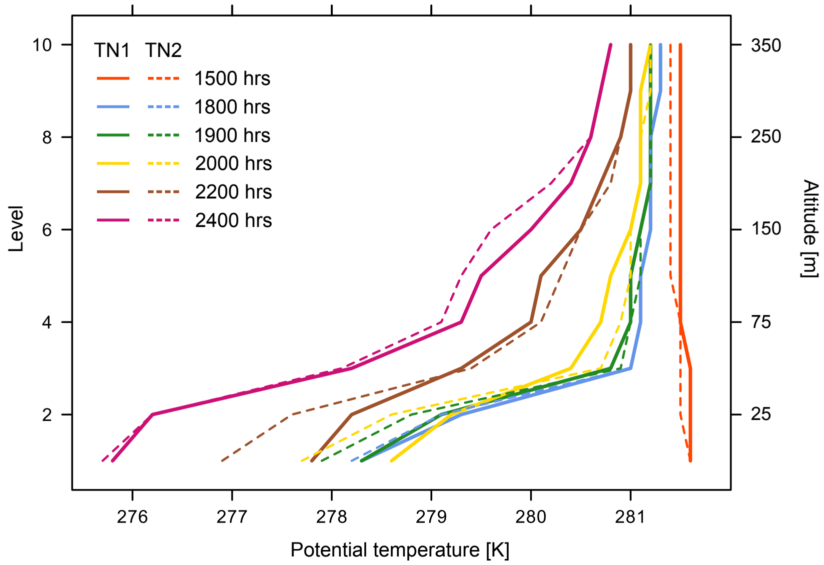

Figure 4.11: Vertical profiles of potential temperature from the centre of domain 4 over the lowest 10 model levels at 1500 hrs (red), 1800 hrs (blue), 1900 hrs (green), 2000 hrs (yellow), 2200 hrs (brown) and 2400 hrs (purple) for TN1 (solid lines) and TN2 (dashed lines). Altitude corresponding to vertical levels is shown on the right axis.

air masses of opposing flow direction. The model provides the opportunity to examine atmospheric stability at a much more detailed level than the observations taken at Coles Place allow. Figure 4.11 provides vertical profiles of potential temperature extracted from the centre of the innermost domain (approximately the location of Coles Place). It is shown that simulation TN2 produces greater low level stability than TN1, which is in line with the observations taken at Coles Place. The reason for the decreased stability in TN1 can be attributed to reduced heat loss in the lowest two grid levels between 1800 hrs and 2000 hrs. Profiles during the early stages of the simulation are similar (1500 hrs) and towards the end (2400 hrs) they are also aligned well. It is indicated through the enhanced cooling in the levels above (especially apparent between level 3 and 6 at 2000 hrs), that the observed discrepancy between profiles during the period 1800 hrs to 2200 hrs may be a result of increased heat supply from higher levels and thus a product of increased turbulent activity. However, assimilated wind speeds in the case of TN1 are lower than those for TN2 and so is the turbulent kinetic energy (TKE) as simulated by TAPM for the lower levels (not shown). Therefore, no solid conclusions as to what process is responsible for the observed enhanced surface cooling in TN2 can be drawn. Agarwal et al. (1995) and Sharan et al. (2003) both found reduced sensible heat fluxes under stable nocturnal conditions, when wind speeds are low (< 1 m/s and < 2 m/s, respectively) due to damped turbulent heat exchange. This might provide a potential explanation for the increased stability seen in both observations and predictions for TN2, but without further investigation, no solid interpretation of the observed mechanism is possible. This, however, is beyond the scope of this analysis. Spronken-Smith (2002) investigated energy flux partitioning in Christchurch in the suburb where Coles Place is located and reported low sensible heat fluxes under very stable nocturnal conditions during winter, but no reference is made to the variation in fluxes under varying flow intensity.

More important for the focus of this study, is the effect that the low level meteorology has on resulting temporal variation in PM_{10} concentrations. Figure 4.10 already provides good evidence that the observed difference in temporal variation in PM_{10} concentrations between TN1 and TN2 results from different dispersion mechanisms, as the simulated emission release was identical in both cases. To gain further insight into the disparity of dispersion processes between the two cases, forward trajectories were analysed for the two cases. Figure 4.12 shows these for both simulations. Time of release is 1800 hrs, just before peak emission release. Trajectory paths are shown until the end of the simulation at 2400 hrs. Due to the lower wind speeds in TN1, particles do not get dispersed as much (they do not travel as far to the west) as they do under conditions simulated for TN2, which results in enhanced accumulation of particulates in the urban atmosphere in this case. Furthermore, recirculation within the katabatic drainage occurs earlier, so that these particles follow the northern branch of low level flow splitting around Banks Peninsula that these katabatic winds are subject to. Thus, a higher amount of particulates is re-advected over the city. In the case of TN2, trajectories show that particles released in the western regions of the urban area are likely to travel far enough with the prevailing north-easterlies, so that

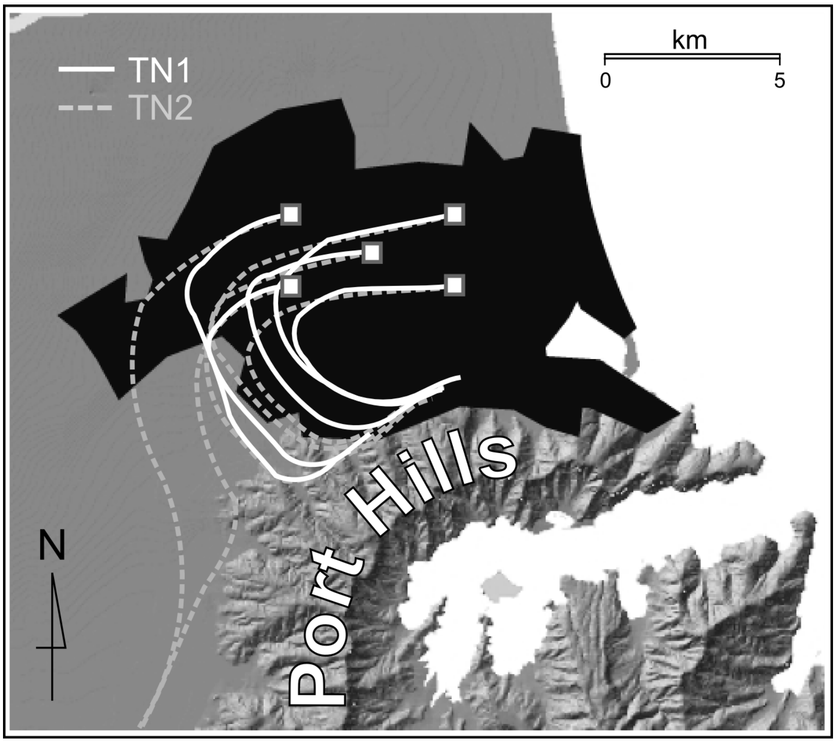

Figure 4.12: Forward trajectories for simulations TN1 (solid white lines) and TN2 (dashed grey lines) from 5 release points over central Christchurch. Time of release is 1800 hrs. Trajectories shown until end of simulation at 2400 hrs.

recirculation does not occur at all. Instead, these particles are advected to the south following the southern branch of the above mentioned flow splitting. Particles released further to the east in simulation TN2 are still likely to be recirculated across the city, although, this occurs at a later hour and therefore does not produce such increased particulate levels as observed under dispersion conditions associated with TN1.

In summary, the results of the idealised case simulations support the argument that the timing of the transition between day-time north-easterlies and night-time westerlies over Christchurch plays a crucial role in controlling the accumulation of particulate matter during the evening. Worst conditions are to be expected when the transition occurs shortly after the time of peak emission release, as the identified mechanism favours pollutant build up through flow stagnation and subsequent recirculation. In case of delayed flow reversal, enhanced dilution and delayed recirculation favour cleaner air, as particles are less concentrated and also less likely to be re-advected across the urban area. In case of a transition occurrence before emission release peaks, rather quick dispersion out to sea through more or less constant north-westerly airflow can be expected, although this has not been investigated. This, however, depends on the air mass characteristics of the density current that was formed some distance away from the city, and might be subject to modification along the way, and highlights how mesoscale influences add to the complexity of local air pollution meteorology.

4.4 Conclusion

In this chapter it was found that the local meteorology described by the classification produced in Section 3.2.2 is, at least for the two high pollution classes, describing distinctly different low level airflow conditions, which are associated with different mesoscale dispersion mechanisms. It was shown that the timing of low level flow reversal in the evening is a very crucial factor that controls pollution dispersion in Christchurch. A flow transition that occurs shortly after the time of peak emission release can be expected to produce some of the worst air quality in the city. Flow stagnation with associated low wind speeds restricts dilution and produces a sharp short increase in PM_{10} concentrations. Subsequent flow reversal causes pollutants to be re-advected across the urban area, which can extend the period of degraded air quality into the early morning hours. Should this transition occur later, it can be expected that concentrations follow the signal of emission release more closely with a distinct maximum a few hours after peak release, and a steady decrease thereafter, due to enhanced dilution through persistent low level flow conditions.

The numerical modelling described in this chapter was able to show that observed differences in PM_{10} concentrations can indeed be attributed to meso- to local scale atmospheric control mechanisms rather than varying emissions. TAPM was able to reproduce the differences in the temporal concentration signal observed in the measurements between two idealised scenarios, although emission release was identical in both cases. It is very encouraging to see that a novel climatological approach to numerical modelling, as implemented in this chapter, proved to be successful in capturing atmospheric processes that govern particulate matter dispersion in such great detail. The simulation results enabled the examination of fundamental atmospheric processes in a three dimensional manner for idealised (climatological) case studies. This would be impossible to achieve through real-world measurements, as it is simply not feasible to collect high resolution three dimensional atmospheric data over extended time periods that enable the assessment of generalised mechanisms on climatological time scales. However, the approach taken here needs to be applied to a wider range of analyses in order to gain confidence in its reliability. It may just have been a lucky strike that predicted and observed concentration patterns match this well in the case of Christchurch, but it surely increases confidence in the reliability of the air quality classification produced in Section 3.2.2. The fact, that averaged differences between two classes can be simulated in an idealised numerical prediction environment, certainly indicates that the classification accurately identified fundamentally different meteorological conditions with regard to their influence on air quality. Apart from the modification through data assimilation, low level flow in this modelling exercise is solely driven by topography and surface induced thermodynamics. It is expected that information on differences in vertical atmospheric structure during different low level flow regimes would enhance the accuracy of predicted surface wind field patterns and therewith increase understanding of dispersion mechanisms. Nonetheless, results are promising and certainly provide further insight into principle mechanisms of atmospheric controls on air quality in Christchurch.

From a regulatory point of view, the results presented in this chapter may not be of direct value. However, two aspects of this investigation might be useful for local authorities. Firstly, as shown in Figure 4.10, it is indicated that the diurnal emission profile that was provided by ECan may be an unrealistic representation of actual emission release with regard to magnitude and timing of emissions during the late afternoon/evening. Secondly, and more generally, the findings of this investigation surely add to the general understanding of different dispersion processes in Christchurch, especially under conditions that are most conducive to increased levels of particulate pollution. This may prove to be a valuable extension of the knowledge base for local authorities and might become useful in, for example, future attempts to implement pollution forecasting for Christchurch.

In summary, this chapter has shown how mesoscale processes influence air quality through air mass interaction and associated dispersion mechanisms. The next chapter will provide a further step to producing a climatological assessment of air quality in Christchurch by investigating influences that originate at a synoptic scale.

Chapter 5

Synoptic controls and historic pollution potential

So far, atmospheric influences on PM_{10} pollution in Christchurch have been analysed and quantified on local to regional scales over a time period covering the last decade. This chapter will extend this investigation in both space and time. First, synoptic influences are analysed with regard to their governing control on producing local meteorological conditions that are conducive to elevated levels of particulates. Afterwards, historic variability in pollution potential as represented by atmospheric proxies is examined. Finally, a brief analysis of potential influences of low frequency climatic signals that operate on hemispheric to global scales is carried out, before projected future changes in synoptic conditions are briefly discussed in the light of the results of previous sections. Additionally, a detailed discussion of data quality and availability and its influence on the presented analyses is also given in this chapter.

5.1 Synoptic controls

To investigate meteorological influences on air quality that result from atmospheric processes on coarser spatial scales, terminal nodes from the classification produced in Section 3.2.2 were analysed with regard to their synoptic forcings. As no information on PM_{10} concentrations is needed for this analysis, it was decided to extend the period used to investigate synoptic influences over a slightly longer time period to try to capture variability associated with longer term influences such as ENSO. Thus, the analysis presented here is based on daily meteorological observations between 1995 and 2008.

Based on cluster analysis of 1000 hPa height fields derived from NCEP/NCAR re-analyses (Kalnay et al. 1996), Kidson (2000) identified twelve synoptic classes and related them to New Zealand weather regimes using temperature and precipitation observations (Figure 5.1). This classification has been used in several studies to assess general and/or long-term synoptic influences for a variety of applications (e.g. Beentjes & Renwick 2001, Jiang et al. 2005). It is available from 1958 to the present day and each day is classified into one of the twelve classes at 1200 hrs and 2400 hrs. Kidson (2000) concluded in his study that, given that the spread of climatic elements within classes is large compared with the differences between classes, this synoptic climatological classification is mainly of qualitative value. However, he also stated that there may be applications in which the classes will be of quantitative value, as for example in frequency analyses of extreme events.

The NCEP/NCAR re-analysis is a three dimensional gridded atmospheric data set that was first introduced to the international scientific community by Kalnay et al. (1996) and has been cited more than 7000 times in scholarly articles since then. It is probably the most commonly used set of a number of re-analyses that have been created within the last 20 years. The general idea of re-analyses is to provide a spatially homogeneous standard set of atmospheric observations that assures comparability across the globe, so that global climate analyses do not suffer from biases introduced through e.g. different instrumentation, differences in measurement techniques or different measurement intervals. Essentially, these re-analyses are the output of General Circulation Model (GCM) hindcasts into which large sets of atmospheric observations for a given time period have been assimilated. Assimilated measurements for the NCEP/NCAR re-analysis include, among others, surface station measurements, ocean buoy data, atmospheric soundings and satellite observations collected across the globe by various national meteoro-

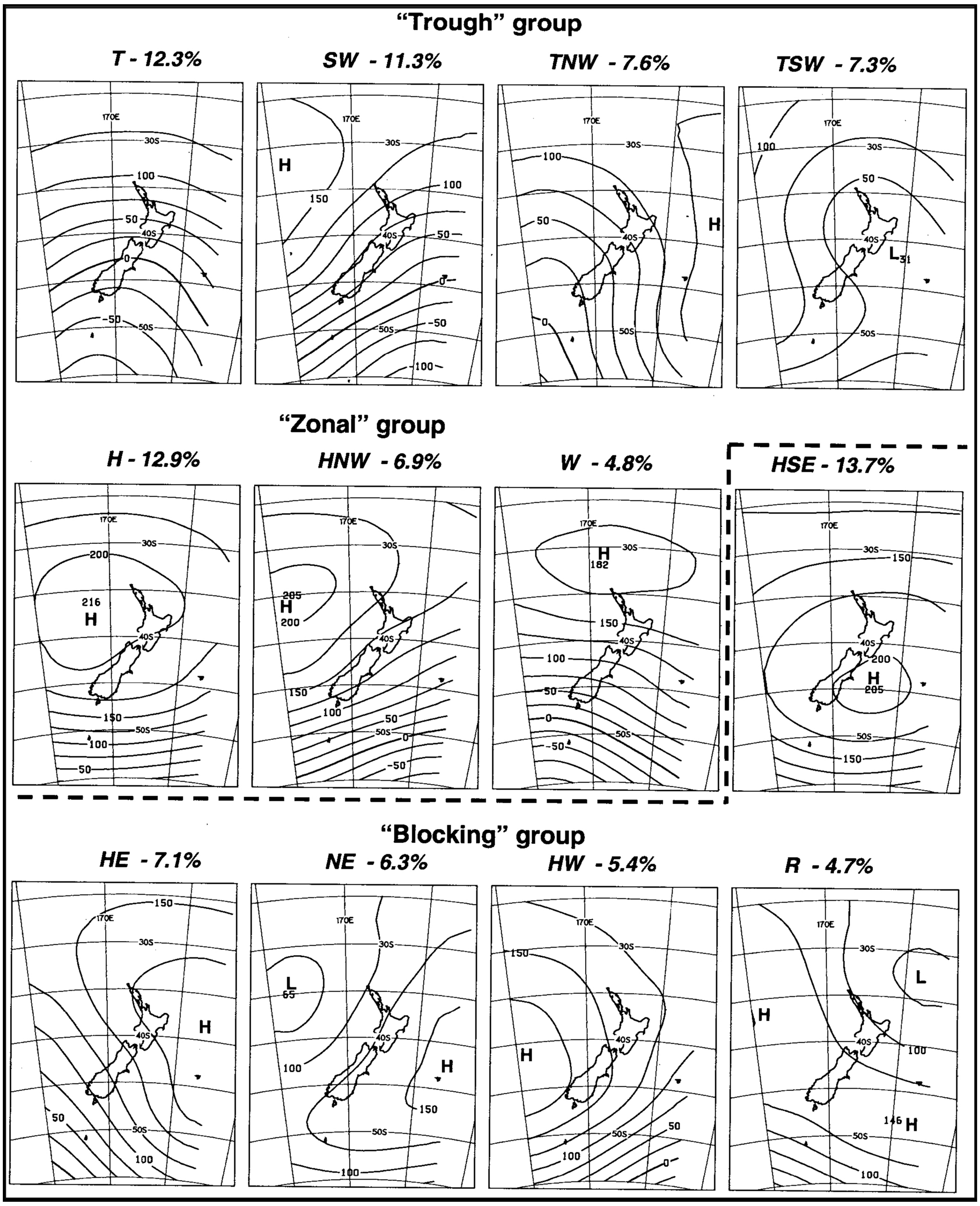

Figure 5.1: Synoptic types as identified by Kidson (2000). Percentages denote climatological frequency of types. For an explanation of the groupings, refer to original text.

logical institutions. Brian Giles from the University of Birmingham provided a comprehensive summary of the history and general character of the various re-analyses in Bridgman & Oliver (2006).

This section utilises the synoptic classification of Kidson (2000) in both a qualitative and semi-quantitative way. Frequency analysis of synoptic types is used to relate synoptic flow patterns to local atmospheric conditions to gain a general understanding of synoptic controls. Furthermore, major temporal synoptic progression patterns are analysed and related to local air quality.

As local atmospheric conditions that lead to deterioration in air quality can be considered extreme in the sense that only a narrow range of local meteorological conditions will restrict dispersion sufficiently to permit the build up of ambient pollutants, according to Kidson (2000), a quantitative investigation should generally be possible. Even though none of the identified splits in the classification tree analysis are located at extreme ends of the distribution of the respective predictor variable, the combination of splits that are applied to isolate atmospheric conditions of TN1 & TN2 can be considered extreme. Both of these classes represent cases which account for less than ten percent each of the total data set.

Figure 5.2 shows the relative increase or decrease in frequency of the set of 12 synoptic types identified by Kidson (2000) within each of the terminal nodes in comparison with their overall distribution for both 1200 hrs and 2400 hrs (the times for which synoptic types are classified each day). The further a box deviates from the line of expected frequency distribution, the stronger the relationship between the synoptic type and the exceedence probability class. The width of the boxes is proportional to their overall frequency adjusted to the terminal node frequency, so that the ratio of widths between all synoptic types within each TN, as well as the frequency of each synoptic type across TNs is kept constant. These association plots were created using the 'vcd' add-on package for R developed by Meyer et al. (2006) and Meyer et al. (2009). The colour shading relates to the strength of dependence between the considered categories and is, simply speaking, a visualisation of significance levels based on Pearson residuals (Zeileis et al. 2007). The colour key to the right of each panel in Figure 5.2 defines the direction of the resid-

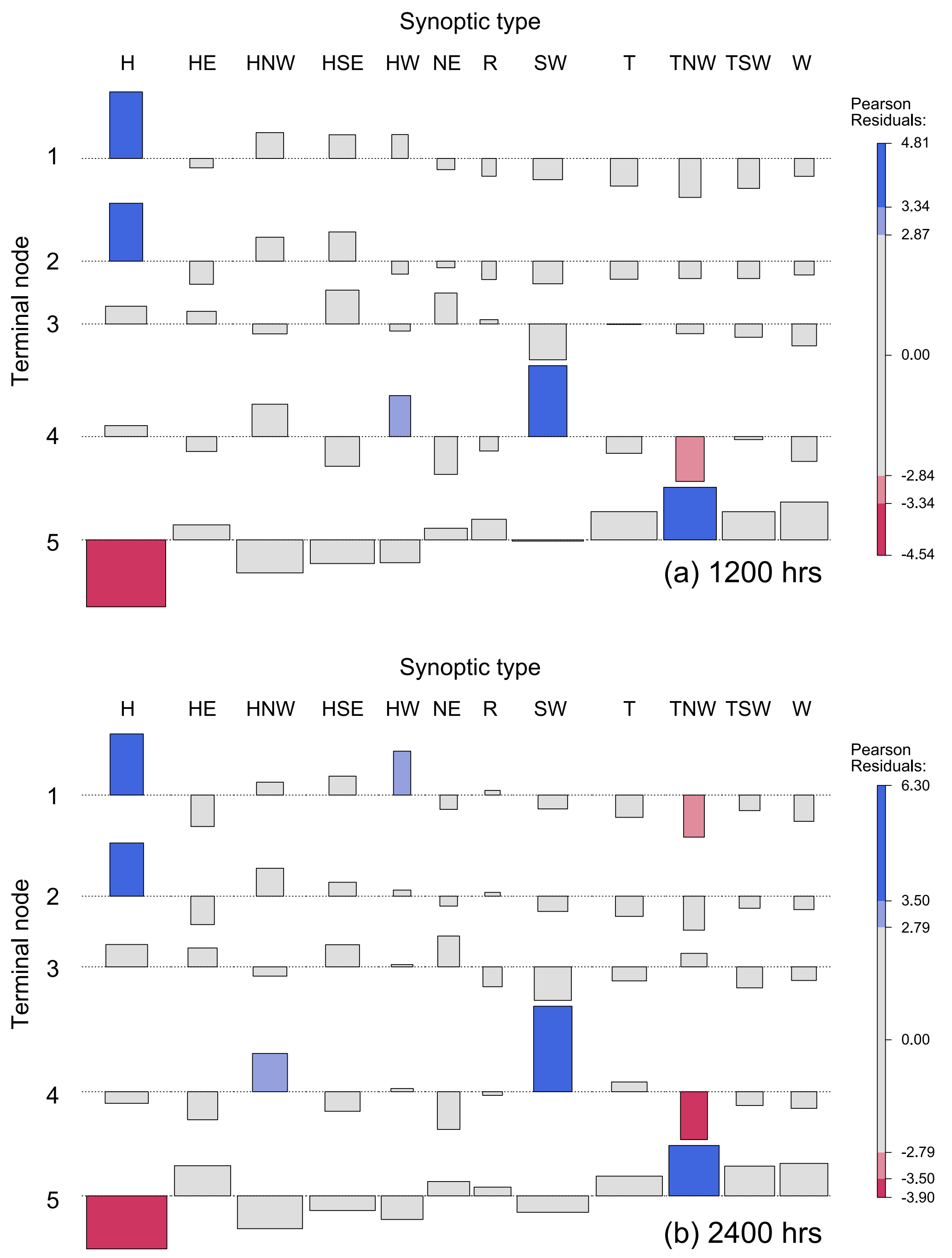

Figure 5.2: Association plots of dependence between TNs and synoptic types for (a) 1200 hrs and (b) 2400 hrs. A description of the (residual based) shading is given in the text.

uals (colour) and the level of significance (shading) and shows the maximum positive (blue) and maximum negative (red) residuals. Grey indicates no (significant) dependence, light colour shading indicates significance at $p < 0.1$ and dark colour shading denotes high significance at $p < 0.01$. For an in-depth description of the residual based colour shading refer to Zeileis et al. (2007).

For both daily synoptic classifications (1200 and 2400 hrs), the pattern is similar, although slight differences are apparent. Given that for the isolation of terminal nodes one and two local wind conditions during the evening are most important, greater focus is given to synoptic conditions at midnight. However, the dynamics of progression between different synoptic conditions is also important and will be analysed later. It is obvious that the two high pollution classes are dominated by anticyclonic conditions with a high pressure system located over the Tasman Sea in close vicinity to New Zealand, denoted by the highly significant increase in the occurrence of synoptic type H, and also HW in TN1 (although less significant). It is suggested that latitudinal variation in the location of this anticyclone is of importance, given the decreased dependence of TN2 on HW. Furthermore, although not statistically significant, synoptic conditions with anticyclones located close to the east of the country, represented by HSE, show increased frequencies. Additionally, again not statistically significant, a decrease of types that promote southerly to westerly flow (TSW, SW, W, T) and of types with north-westerly flow directions (HE, TNW) is observed. A summary of synoptic influences for each terminal node is given below.

TN1 local atmospheric conditions are mostly a result of anticyclones located in close vicinity to the west of the country (H, HW) or directly over the (eastern) South Island (HSE).

TN2 similar to TN1, although the high pressure system over the Tasman Sea is likely to be located slightly further north as indicated by increased frequencies of HNW and W at the expense of H and

HW. This leads to an increased isobaric gradient over the South Island which may explain the slightly windier conditions for cases classified in this node when compared to TN1. In Section 3.2.2, it was found that TN2 was more regularly associated with north-easterly flow during the evening hours. This, given the identified synoptic signature, is likely to result from the formation of a lee-trough in response to orographic large scale flow modification, as described in McKendry (1985).

TN3 no significant signal is apparent. However, all synoptic types that show anticyclones located to the east of New Zealand show increased frequencies (HE, HSE, NE, TNW).

TN4 atmospheric conditions in Christchurch as described by TN4 are clearly associated with south-westerly flow, with significantly increased frequencies of HNW and SW and a marked decrease in types promoting northerly to north-westerly flow (HE, NE, TNW).

TN5 is dominated by flow from northerly quadrants (HE, NE, TNW), but also a result of enhanced frequencies of situations that favour zonal flow over the South Island (T and W $\rightarrow$ westerlies, TSW $\rightarrow$ easterlies).

In summary, the local meteorological conditions in each TN as identified by classification tree analysis can be clearly associated with distinct synoptic patterns that control large scale air flow, in response to which local meteorology is modified. However, these synoptic forcings are not stagnant over time and their temporal evolution results from smooth transitions from one state to another. This is examined in more detail in the following section.

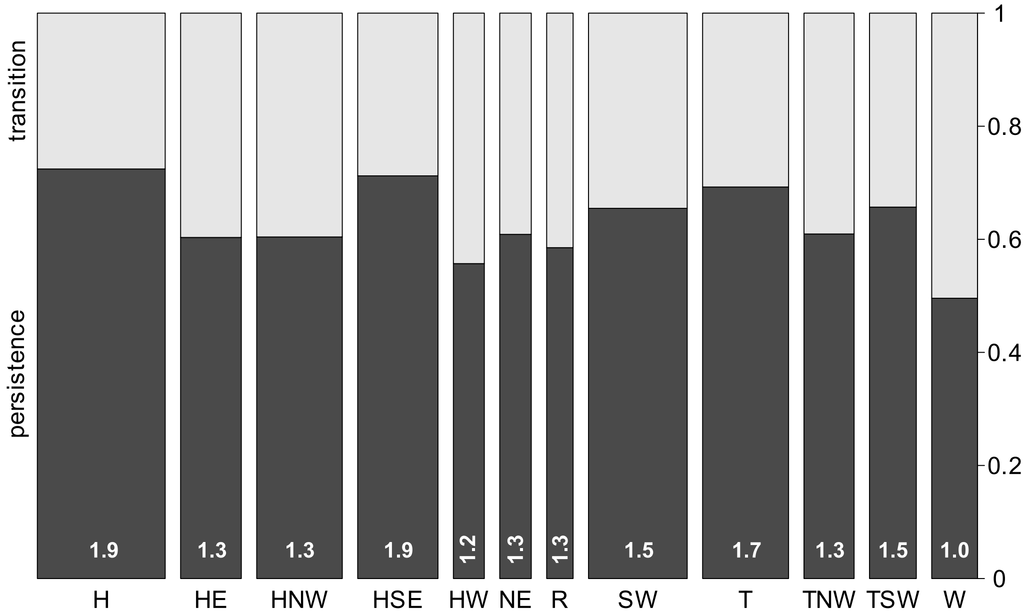

Figure 5.3: Spine plot showing relative frequencies of transition (progression to different type) and persistence (no progression) for each synoptic type for the months May - August between 1995 - 2008. Widths of boxes are proportional to absolute frequency of each type. The mean time in days that each type persists is shown as white numbers at the bottom of each bar.

5.1.1 Transitional patterns

In order to get a clearer understanding of the temporal dimension, it is important to investigate average persistence of synoptic types and likely transitions between them. Figure 5.3 summarises relative frequencies of persistence and transition, as well as the mean time of persistence in days for each synoptic type. Frequency counts were derived from the time series of synoptic types by comparing each observation i to its immediate successor $i+1$. Equality between i and $i+1$ was defined as persistence, a change in type between i and $i+1$ was counted as transition. The most dominant type, in both absolute frequency and persistence duration, is type H. In addition to H, winter months are dominated by HSE, SW and T, which is in line with the findings of Kidson (2000). Even though HNW also occurs frequently, this synoptic type tends to progress quicker towards other types (i.e. it is less persistent).

True transitions types are HW, NE, R and especially W, which on average only persists for approximately 24 hours. For his classification, Kidson (2000) analysed the most common transitions between synoptic types and concluded that the strongest transition patterns are in line with expectations from synoptic experience. However, Kidson (2000) has taken into account all seasons to analyse the common patterns of transition between the types, whereas the analysis presented here is restricted to the months May - August. Additionally, he outlined that there are significant seasonal differences in the frequency of the types. Therefore, the main transition patterns were analysed for the data used here in order to find common features in synoptic evolution with respect to air quality in Christchurch.

Figure 5.4 summarises these transitions by assigning a probability that denotes the likelihood of one type being followed by another. This reveals that between May - August the most common transition is T → SW → HNW → H → HSE → HE → TNW → T (taking the highest transition probability as a starting point). This is completely in agreement with the most common transition pattern identified by Kidson (2000). Figure 5.5 shows this transition in more detail, along with pollution potential indicated by association with terminal nodes from the classification tree analysis at each stage, as identified in Figure 5.2. This transition depicts the eastward progression of a high pressure system embedded in the mid-latitude westerlies en route from the Tasman Sea, crossing New Zealand and finally leaving the region towards the east. As a result of the meandering of the predominant westerly flow in the region, the loca-

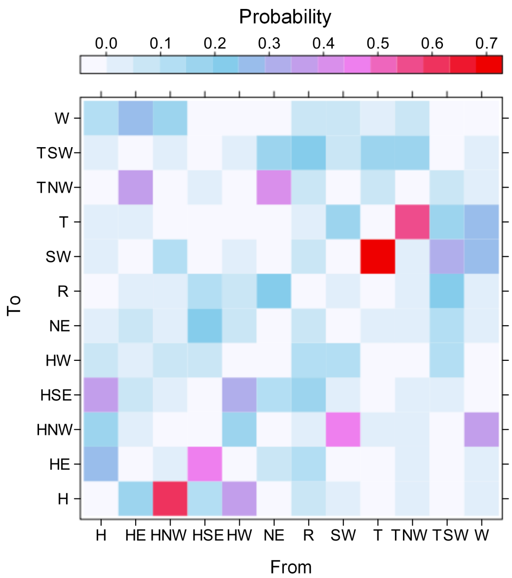

Figure 5.4: Probability of transitions between synoptic types as identified between May - August for the time period 1995 - 2008.

tion of the anticyclone is subject to meridional variations in its location at any stage during its eastward propagation. This may result in alternative transition patterns such as T → SW → HW → HSE → NE → R → TSW → SW, for example. This transition is the realisation of a anticyclonic passage that is pushed further south due to the presence of cyclonic features in its wake and/or to the north(east). Similarly, the anticyclonic passage may be shifted northward, then most commonly following a transition pattern T → SW → HNW → W → T. It needs to be pointed out that these transitions are not always strictly forward. Some stages may be skipped and it is also very common to find two (or more) synoptic stages oscillating between each other over some period of time.

5.1.2 Air quality in relation to synoptic progression

With regard to air quality, the described transition patterns show varying potential for degradation. The most common transition has a clear tendency to create local atmospheric conditions that are conducive to elevated levels of particulate matter during its intermediate stages (H, HNW and HSE). These are usually followed by conditions promoting north-westerly flow which, in the case of the Canterbury region, are mostly associated with lee side foehn conditions, and hence a clearing of the atmosphere. In the case of a southward high pressure passage, HW and HSE are the situations with enhanced pollution potential. However, as mentioned earlier (see Figure 5.3), HW generally shows transitional character. Additionally, the final stages of this progression (R, TSW) generally produce easterly flow in the region which is regularly associated with cloudy, windy, and possibly rainy conditions. Therefore, this transition can be expected to be more favourable for enhanced air quality. Finally, the transition describing the northward anticyclonic passage can be assumed to yield the least potential for degrading air quality in Christchurch, mostly because the anticyclonic influence is generally smaller, as it is further away. It is, however, crucial to bear in mind that the discussed transitions are highly idealised cases and day-to-day variation among these synoptic sequences is high.

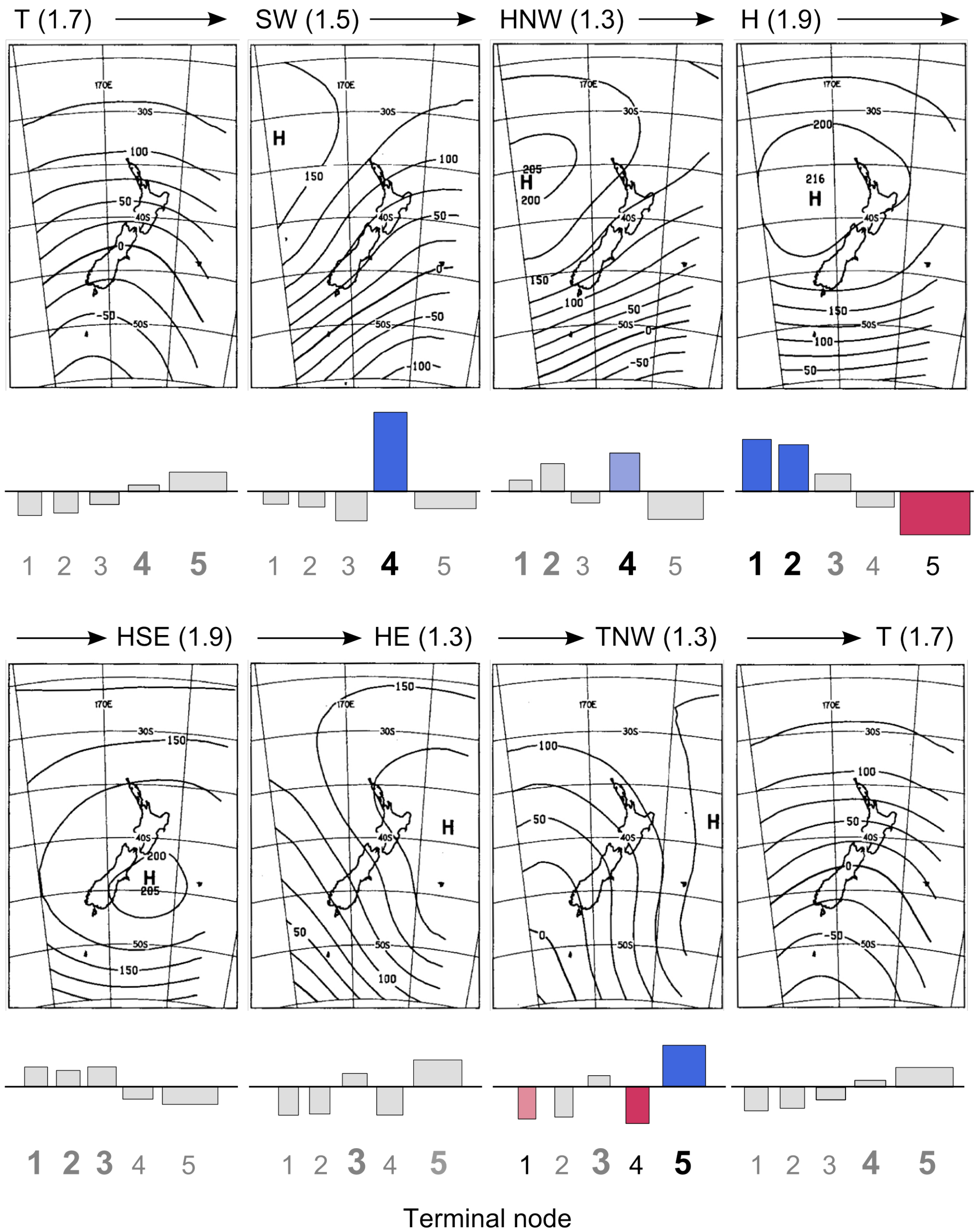

Figure 5.5: The most common transition pattern of synoptic progression during winter. Headers of synoptic charts show the name of the synoptic type and mean persistence in days. Bar plots below charts depict association of synoptic type with terminal nodes. Labelling of nodes refers to direction (size) and magnitude (shade) of dependence.

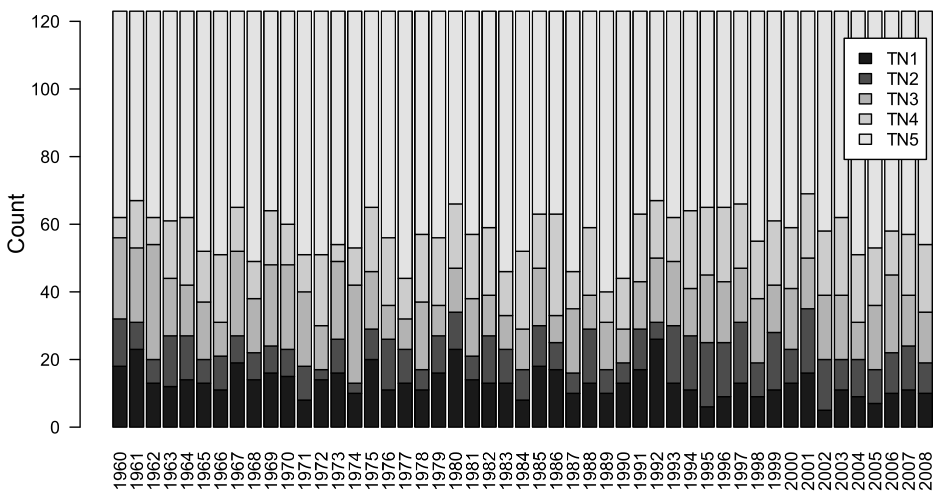

Figure 5.6: Frequency of terminal nodes between 1960 - 2008.

5.2 Historic pollution potential in Christchurch

In order to put recent monitoring results into a wider historic context, this section examines the year-to-year variations in atmospheric conditions with regard to the identified influences on air quality in Christchurch over the last 50 years. The aim is to assess how atmospheric conditions over the last decade (the period of quality assured PM_{10} monitoring) relate to conditions in the past and whether longer term or low frequency climatic influences can be determined. In light of the satisfactory performance of the pollution potential classification, it is utilised as a proxy and is believed to present an accurate measure of historic year-to-year variability in air quality. As Kidson (2000) utilised NCEP/NCAR re-analysis data, the available record of twice daily synoptic type classification spans from 1958 to present day. Local atmospheric observation recording at Christchurch airport began on 31st December 1959 (CliFlo). Hence, this study assesses historic pollution potential for the period 1960 - 2008. Figure 5.6 shows the predicted yearly frequencies of terminal nodes identified through classification tree analysis (Section 3.2.2) for this period. With regard to TNs 1 and 2, variability is high with some years predicting up to twice as many occurrences than others. However, given that the predicted frequencies are based on hourly meteorological observations that span nearly five decades, a careful analysis of the quality of the data should be carried out. Instrument changes and changes in recording techniques, as well as changes in the surface structure of the surrounding environment of the site location, can all potentially influence the quality and comparability of the data over time. Therefore, the next section provides an in-depth discussion of these issues and the possible influences they might have on the quality of the historic assessment of pollution potential in Christchurch, before further examination of historic variability is carried out.

5.2.1 Data quality, completeness and reliability

One of the most common issues of time series analysis, or any analysis that relies on real-world observations, is the problem of missing data. An in-depth discussion of a great variety of issues relating to this topic can be found in Latini & Passerini (2004). They offer numerous options of identification and remediation of data gaps. One major characteristic that determines treatment of missing observations, is the question whether they are occurring randomly or whether a mechanism can be found that led to the lack of observations (Gentili et al. 2004). Generally, three classes of missing data can be defined in time series analysis:

- *Missing completely at random.* Gaps are independent of the values of the variable in question, any datum in time or values of any other variable. E.g. a bird sitting on a sensor.
- *Missing at random.* Gaps are independent with respect to the values of the variable in question, but may depend on values of other variables or the datum of the time vector. E.g. periodic shut down of a sensor for maintenance.
- *Non-ignorable missing data.* The gaps are clearly related to the variable in question, are non-random and cannot be predicted by another variable. E.g. extreme recordings that are beyond the scale of the sensor.

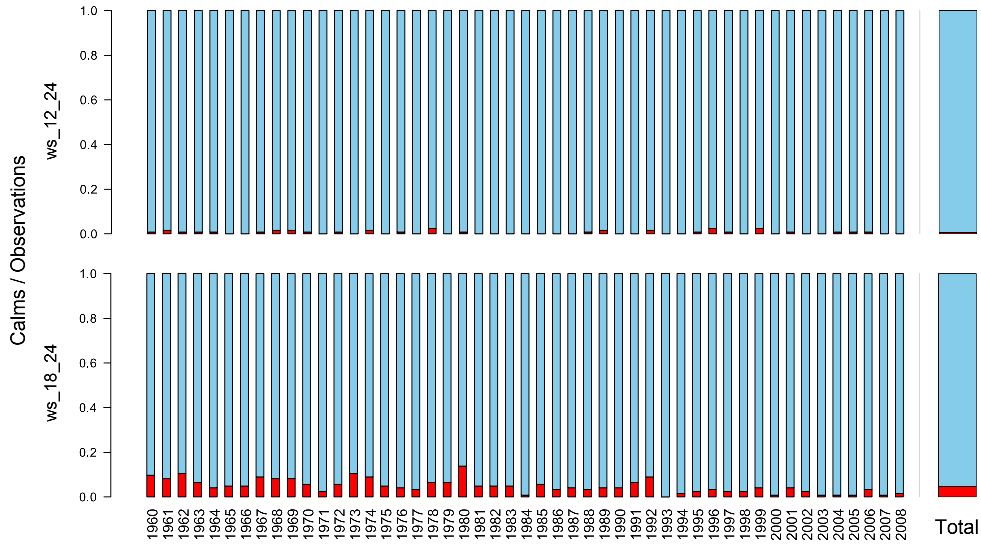

Figure 5.7: Frequencies of hourly calms in daily observations per year for two variables used in classification tree analysis for the months May - August between 1960 - 2008 at Christchurch airport. Red refers to calms, blue denotes non-calms.

Given the use of NCEP/NCAR re-analysis data to produce the synoptic classification, information on gradient flow conditions can be considered to be continuous and need not be checked for data gaps. Hence, it is the information that is used to classify local meteorological conditions that needs to be checked for missing data and possible resultant biases. For *Tmin_i1* no missing data is found. With regard to hourly recordings of wind speed and direction, the matter is more complex. An overview of the proportion of calms in comparison to non-calms for the variables in question is given in Figure 5.7. For *ws_12_24* (upper panel) the proportion of calms is minimal and no particular pattern is apparent. For *ws_18_24* (bottom panel), however, hours classified as calm are more frequent and there is an indication of a step change in the early 1990s. This abrupt decrease in the frequency of calms in the early 1990s for wind speeds averaged over the evening hours is very suspicious. In order to investigate this further, the original hourly observations need to be examined closer. Figure 5.8 shows a very distinct pattern of calms as a function of time of day. Nocturnal observations show

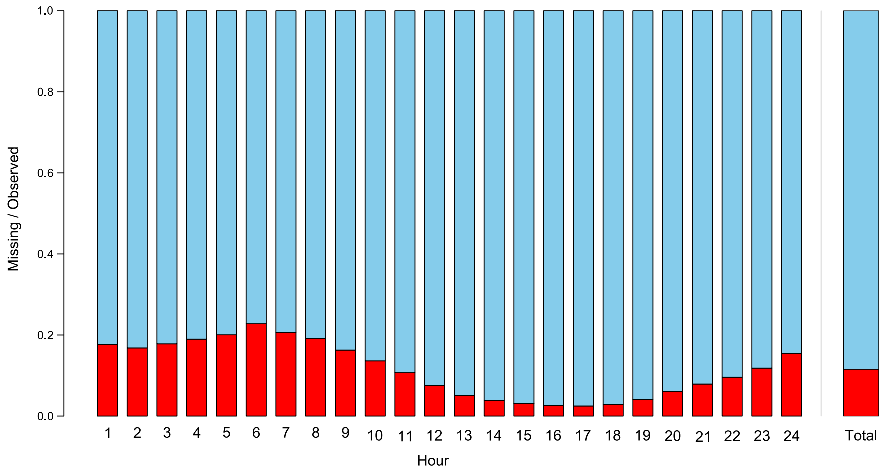

Figure 5.8: Frequency of calms per hour of day for the months May - August between 1960 - 2008 at Christchurch airport.

highly increased numbers (with a maximum at 0600 hrs), whereas observations made during mid-afternoon show the least amount of calms. This is to be expected, as turbulent mixing during day-time is generally higher than at night, due to enhanced thermal forcing. Thus, the general diurnal pattern of clams frequency does not yield any information as to what causes the step change that is apparent in Figure 5.7. However, figure 5.9 shows amount and duration of periods recorded as calm between 1960 and 2008. It clearly highlights the abrupt step change in calms in both frequency and magnitude of duration. In terms of average length of calms (dashed lines in Figure 5.9), the period until 1993 shows an average duration of observed calms of 3.3 hours, whereas after 1993 this drops to only 1.2 hours at a time. An explanation for this sudden change after 1993 is attributable to the implementation of automated meteorological recordings, as outlined in Section 1.3.

A further issue surrounding the recordings of calms is highlighted in Appendix B in an excerpt of a conversation with NIWA, the national institution that maintains "CliFlo: NIWA's National Climate Database on the Web" (CliFlo), the national database for meteorological and climatological data. It highlights the issue that, even in very recent data recordings, data gaps may get incorrectly coded as calms and therewith adds to the uncertainty surrounding the issues of data quality outlined above.

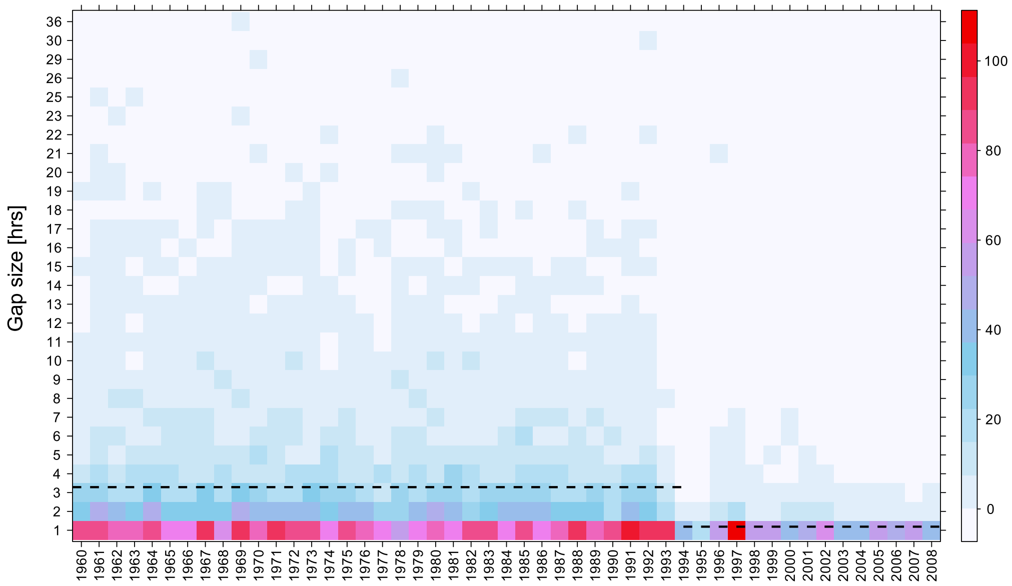

Figure 5.9: Amount and duration of periods classified as calm for hourly wind recordings for the months May - August between 1960 - 2008 at Christchurch airport. Dashed lines indicate mean duration of calms before and after 1993, respectively.

In brief, the combination of a change of the recording method together with potential data mis-classification (missing data being classified as calm - possibly also vice versa) makes investigations prior to mid-1993 rather questionable. Even for the period after the identified step change, potential mis-classifications remain an issue, as can be seen in Appendix B. Even after potential homogenisation of the data segments prior to and after mid-1993, confidence in the quality of the record remains low, as it seems impossible to estimate the proportion, and more importantly, the exact location in time of mis-classified observations within the data. The latter is crucial with regard to the methodology employed here, as this investigation, even though utilising yearly frequencies, is dependent on exact estimations of meteorological conditions at any point in time (at hourly resolution). Potentially, with great care and effort, it might be possible to identify and remedy many of the potential mis-classifications through various imputation methods, but this is beyond the scope of this study. In light of this, no further investigations into the history of the site and its instrumentation was carried out.

In summary, this section has outlined that due to uncertainties surrounding potentially mis-classified wind observations, together with a very prominent inconsistency in the data record, no accurate assessment of historic pollution potential for Christchurch can be carried out on the basis of the results from the classification tree analysis. The resultant bias and uncertainties in relation to local atmospheric conditions are too influential for a meaningful examination of year-to-year variability, where small changes may be of importance. There is, however, the possibility to assess historic pollution potential on the basis of the findings of synoptic controls on air quality in Christchurch as described in Section 5.1, which is presented in the following section.

5.2.2 Air quality and synoptic and climatic variability

This section provides a brief assessment of longer-term climatic influences on pollution potential in Christchurch. As a direct investigation of long-term variability of local meteorological conditions and resulting expected pollution potential is not feasible due to the issues outlined above, another approach has to be taken. Section 5.1 identified synoptic conditions that tend to favour degraded air quality in Christchurch. Namely, these are synoptic types H and HW, where a high pressure system is located over the Tasman Sea in close vicinity to New Zealand. These synoptic weather situations generally favour light winds and clear skies, thus promote low level atmospheric stability, and in many cases lead to exceedences of the national guideline for PM_{10} concentrations. In fact, in the period 1999 - 2008, 43% of all exceedences were associated with these weather types. Therefore, an analysis of the historic variability of their occurrence during winter time should give a general indication of the long-term variations in air quality in Christchurch. As mentioned in the previous section, no missing values were apparent in the temperature recordings (at least those of minimum temperature). Therefore, a combination of daily minimum temperature values (described by *Tmin_i1*) and the mentioned synoptic weather situations (which accounts for 66% of all exceedences between 1999 - 2008), should provide an acceptable approx-

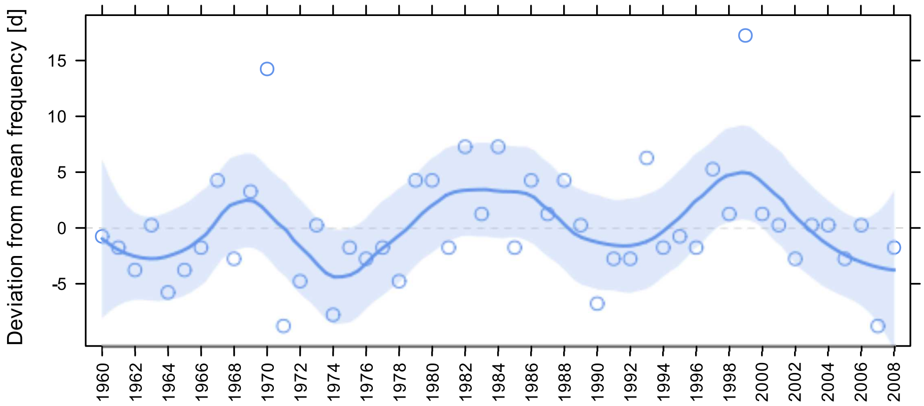

Figure 5.10: Variability in frequency of occurrence of days classified as H or HW with *Tmin_i1* < -0.1 °C for the period May - August 1960 - 2008 (circles). Line denotes smoothed signal (locally weighted polynomial regression with a smoothing parameter $\alpha = 0.3$, corresponding to a span of 15 years). Shaded area shows 0.95 * SE (standard error) of the regression estimation.

imation of historic pollution variability. Figure 5.10 shows frequency count deviations from their overall mean of all days for the 123 days between May and August of each year between 1960 and 2008 with *Tmin_i1* < -0.1 °C and synoptic conditions classified as either H or HW (hereafter referred to as HHWT). The smoothed signal was calculated employing a locally weighted polynomial regression model (Loess), which was first introduced by Cleveland (1979). Loess is a non-parametric regression fit technique that produces a smoothed model surface by fitting a local least squares regression model. Fitting is achieved by using a specified number of explanatory variable values in the neighbourhood of the point to be estimated (the 'span' - specified through the smoothing parameter α, which depicts the fraction of the data to be considered). Additionally, weights are assigned to each of these neighbourhood points, so that values near the estimation point have more weight than points located further away (e.g. Venables & Ripley 2002 or Crawley 2005). In the case of Figure 5.10, the regression model was fitted with a smoothing parameter $\alpha = 0.3$ (corresponding to a span of $49*0.3 \approx 15$ years). Standard setting of Loess smoothing in R was used for the weights. In fact, for all subsequent analysis using Loess, standard R settings were

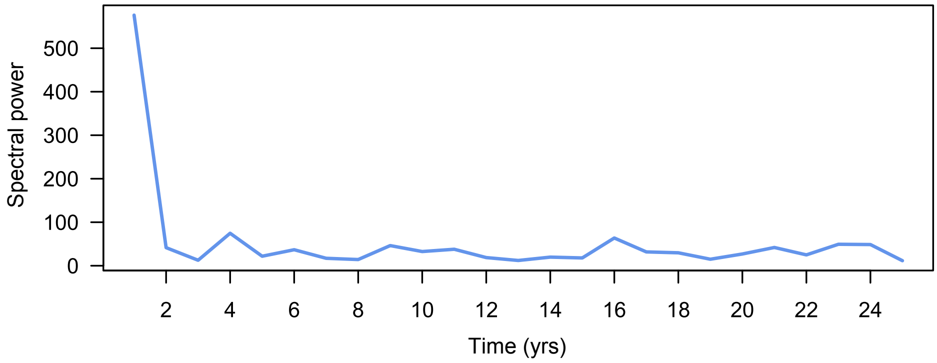

Figure 5.11: Discrete fourier transform of the HHWT signal.

applied for all parameters (including weights), and only α was adjusted. A clear periodicity is apparent in the frequency of the synoptic types in question. Peak occurrences are seen for the late 1960s, the mid-1980s and the late 1990s. Relatively few occurrences are evident in the mid-1970s and early to mid-1990s. Discrete fourier transformation (implemented using the fast fourier transform function in R) of the raw counts indicates weak frequency maxima at 4 years and 16 years (see Figure 5.11). The autocorrelation in time was also assessed (not shown) and reveals a strong inverse correlation ($r \approx -0.5$) every eight years, which is in line with the 16 yr signal identified through fourier transformation. A more detailed analysis of possible climatic influences that are associated with the observed periodic signal is given later. With regard to the first objective of this study, the years between 1999 - 2008 are of high interest. Figure 5.10 shows a decrease in occurrences of HHWT for this period. Similarly, in Section 3.2.3, a clear decreasing trend in PM_{10} concentrations over this period was found, thus indicating that the identified decrease in concentrations may actually be a result of fewer occurrences of weather types that promote degraded air quality, rather than a result of decreased emissions as concluded in Section 3.2.3. However, care needs to be taken when interpreting Loess models near the end of a time series, as confidence in the prediction decreases due to fewer points being available for the fit. This is seen as the widening of the shaded area in Figure 5.10 that denotes 0.95 * SE (standard error) of the model prediction. Therefore, interpretation of the indicated trend towards the end of the series is prob-

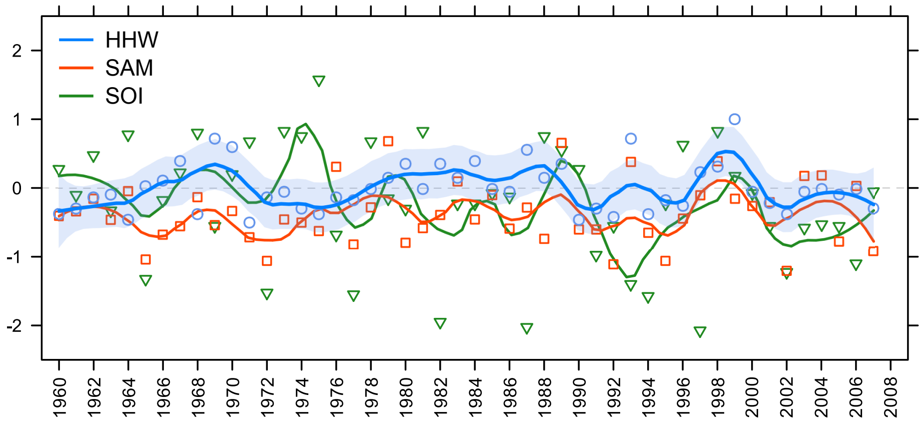

Figure 5.12: Comparison of periodicity between HHW (blue), SAM (red) and SOI (green). Smoothing is achieved through Loess with a smoothing parameter $\alpha = 0.2$ (span $\approx$ 10 years). Shaded area denotes 0.95 * SE of HHW signal.

lematic. Furthermore, both analyses partially use *Tmin_i1* as an indicator of local meteorological conditions. Therefore, these analyses are not independent from each other and may simply depict the same signal as a result of the use of identical information.

As a consequence, the long-term investigation of climatic synoptic variability was repeated, this time only based on occurrences of synoptic classes H and HW, disregarding the influence of minimum temperature of the following day (HHW). Figure 5.12 shows the variability in occurrence of HHW from May - August for the period 1960 - 2007, along with mean values of the Southern Annular Mode (SAM) and the Southern Oscillation Index (SOI), averaged accordingly (May - August). The reduced time span results from limited availability of information of the low frequency climatic signals after 2007. In this case, a smoothing parameter $\alpha = 0.2$ was employed (span $\approx$ 10 years) to reveal higher frequency periodicity. As the name implies, the SAM is oscillating annually. It describes an oscillation in surface pressure between the mid- and high latitudes of the Southern Hemisphere (Bridgman & Oliver 2006). Its influence on the weather and climate in New Zealand has been subject to numerous scientific studies (e.g. Ummenhofer et al. 2009 or Clare et al. 2002). During austral winter it is usually in its negative phase, which explains the mostly negative values in Figure 5.12. It becomes apparent, however, that this mode also shows a periodic signal of about 4 - 6 years on an interannular scale. Furthermore, it is evident that, apart from the period between the mid-1970s and the early 1980s, the HHW signal is mostly in phase with the SAM, especially after 1983. It is not clear what causes the signal to be out of phase during the mid-1970s to early 1980s. No clear relationship is seen for the SOI. However, it is indicated that, in general, positive SOI values seem to favour the occurrence of synoptic types H and HW. This might provide an explanation for the observed phase discrepancy between HHW and SAM signals, at least during the mid-1970s, where a distinct peak in the SOI is apparent. However, an in-depth analysis of climatological forcings on New Zealand weather is beyond the aim of this study.

Finally, a very brief investigation of projected changes in synoptic frequencies is given here to assess potential future changes in expected air quality in Christchurch. Mullan (2009) examined expected frequency changes of the synoptic types described by Kidson (2000) at the end of the 21st century. His findings for the winter season are summarised in Figure 5.13. The box plot denotes expected seasonal changes in type frequency that were calculated as follows. Daily mean sea level pressure fields (MSLP) from ten GCMs for a 40 year simulation in the 20th century (commonly known as the '20c3m' run) were classified according to the classification introduced by Kidson (2000). Similarly, Kidson types were diagnosed from daily MSLP fields for a 20 year simulation of the same ten GCMs at the end of the 21st century (2080 - 2100) using the IPCC SRES A1B emission scenario to force the models (the 'sresa1b' run). Then, seasonal frequencies for all synoptic types across all ten models for both periods were calculated. Finally, seasonal differences in frequencies were calculated (sresa1b - 20c3m) to provide the changes seen in Figure 5.13 (Brett Mullan, pers. comm.).

With regard to the focus of this thesis, the change that is of most importance is the increase of synoptic type H during winter. This indicates, that, under an average climate change scenario, it is to be expected that local conditions may become more conducive to elevated levels of particulates in

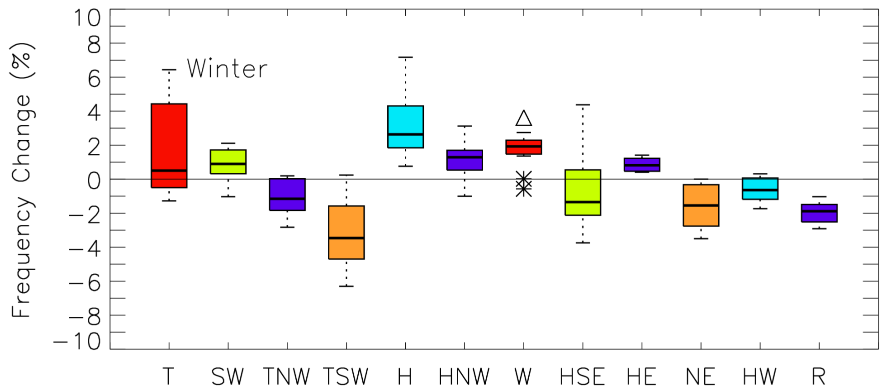

Figure 5.13: Box plots of expected frequency change in synoptic types during JJA at the end of the 21st century. Colour shading has no meaning (Brett Mullan, pers. comm.).

Christchurch, as such conditions are regularly associated with this synoptic type. For the other two important types, HW and HSE, no clear projection of change can be formulated. Types that were identified to be associated with good air quality, such as TNW and TSW, are expected to become less common in the future. To put the expected percentage change into perspective, for the 123 day period between May - August, a 2% change equals 2.46 days. Overall, the projected changes generally paint a mixed picture with regard to expected changes in air quality, as other types that are expected to enhance air quality in Christchurch are projected to become more common, such as T, W and SW. No robust estimates about frequency changes in possible trans-Tasman dust transport events can be given, as no information on expected changes in transitional patterns are available. Therefore, a solid conclusion of expected air quality changes towards the end of this century seems unfeasible. Furthermore, changes to the building structure of Christchurch, technological advances and further regulatory measures over the next decades can be expected to show far greater influence on the pollution problem than the subtle changes in weather type frequencies that are presented here. Finally, it needs to be outlined that the study by Mullan (2009) does not provide any insight of projected changes in synoptic conditions for the period prior to 2080.

5.3 Conclusion

This chapter has investigated influences that control air quality on a variety of coarser spatial and temporal scales. Daily to weekly synoptic controls have been identified and it was shown how variations in their transitional evolution over time influences local air quality. Although direct assessment of historic pollution potential in Christchurch on a local scale was not possible due to issues surrounding data quality and availability, general climatic patterns that are likely to influence air quality in Christchurch have been identified.

Synoptic conditions that promote degraded air quality in Christchurch are mainly associated with anticyclones that are located in close vicinity of New Zealand. It is indicated that conditions are worsened when their centre is to the west of the country. Furthermore, the passage of an anticyclone over the country shows various stages of potential to favour local conditions that promote elevated levels of particulates. In this respect, the latitudinal location of the anticyclonic passage plays an important role. Generally, the further the centre of the passing anticyclone is located away from the Canterbury region and Christchurch, the better the air quality is expected to be. However, the synoptic analysis was based on a classification of highly averaged isobaric surface pressure maps, which means that identified influences can only be of general character and, as outlined by Kidson (2000), variability in the classes is expected to be high. In particular, the influence of the Southern Alps on the mesoscale pressure field is expected to substantially modify the synoptic conditions.

Two of the findings presented in the last section of this chapter are of significant interest for the investigation of historical variation in air quality potential in Christchurch. Firstly, a clear periodicity in the occurrence of synoptic situations that favour local meteorological conditions conducive to elevated levels of particulate matter pollution has been found. Secondly, this periodicity can be explained by interannual variations in winter time intensity of the Southern Annular Mode, at least partly. The former shows that air quality in Christchurch is influenced by processes that operate on interannual hemispheric scales and implies that general pollution potential can be expected to vary on a periodic interdecadal basis. The latter adds to general understanding of the interaction of atmospheric processes that directly and indirectly governs air quality across all scales. Furthermore, with regard to the identified decrease in PM_{10} concentrations over the last decade in Section 3.2.3, Figure 5.12 indicates that conditions at the end of the 1990s were indeed highly favourable for degraded air quality, but since then, there is no evident trend and pollution favouring synoptic weather types have shown approximately average frequency of occurrence in the 2000s. Therefore, it can be concluded that the decrease in PM_{10} concentrations during the last decade is indeed a result of reduced emissions. From a regulatory perspective, this is very encouraging, as it provides further evidence for the success of policy implementation over recent years. However, it can be expected that synoptic conditions may worsen again in the future, which might counter-act these efforts to some degree.

The investigation presented in Section 5.2.2 provides a preliminary assessment of possible climatic influences on air quality in Christchurch, both historically and with regard to expected future climate change. It is by no means an in-depth analysis and needs to be extended in order to draw solid conclusions about mechanisms that operate on hemispheric and interdecadal scales. It provides, however, a very promising insight into potential forcings and projected changes and delivers a good starting point for future analysis of such matters.

Chapter 6

Evaluation of results and assessment of short-term pollution prediction

All the analysis that has been carried out so far has provided useful results with regard to a variety of research questions. Most of these investigations, however, are based on the findings of one analysis, the classification tree analysis presented in Section 3.2.2. The classification obtained from this analysis has yet to be validated and tested for its accurate representation of day-to-day variations in PM_{10} concentrations. The results presented in Sections 3.2.2 and 5.1.2 were derived from data records from 1999 - 2008 and 1995 - 2008, respectively. In order to assess their accuracy and to investigate whether these findings are helpful in predicting pollution potential in Christchurch on a day-to-day basis, they were used to hindcast PM_{10} observations from winter 2009. In order to predict expected air quality for a given day in this period, an exceedence probability index for Christchurch (EPIC) was calculated that incorporates both local and synoptic atmospheric conditions that were identified to be influential on PM_{10} pollution. Each terminal node was assigned a base score depending on its potential to degrade air quality, as identified by the classification tree analysis in Section 3.2.2. These base scores are roughly proportional to the identified exceedence probability for

Table 6.1: Exceedence Probability Index for Christchurch (EPIC) taking into account local meteorological conditions (TNs) and synoptic conditions.

TN	Base score	Synoptic adjustment											
		H (+2)	HE (-1)	HNW (+1)	HSE (+1)	HW (+2)	NE (-1)	R (0)	SW (-1)	T (-1)	TNW (-2)	TSW (-1)	W (-1)
1	8	10	7	9	9	10	7	8	7	7	6	7	7
2	6	8	5	7	7	8	5	6	5	5	4	5	5
3	4	6	3	5	5	6	3	4	3	3	2	3	3
4	2	4	1	3	3	4	1	2	1	1	0	1	1
5	0	2	-1	1	1	2	-1	0	-1	-1	-2	-1	-1

each TN. Afterwards, each base score was adjusted based on the synoptic situation. Adjustment scores for synoptic types were based on their relative importance in TN1 at 2400 hrs, as identified in Figure 5.2. Significant positive (negative) dependence was counted as +2 (-2), while non-significant dependence scored +1 (-1). Synoptic type R was assigned a score of zero as dependency is weak. EPIC scores are summarised in Table 6.1.

Figure 6.1 gives an overview of expected pollution potential coded as EPIC scores versus observed PM_{10} concentration for each day in the period May - August 2009. For each day, synoptic type classification at 2400hrs is shown at the respective score level in blue above or below each bar. Note, axis dimensions for PM_{10} observations and scores are not equal. Therefore, a comparison of magnitude is not reasonable. Apart from a few periods, the general directional pattern matches well, which confirms the findings of Slini et al. (2006) who concluded that CART performs satisfactorily in capturing pollution trends. When expected pollution potential is low, concentrations are low and vice versa. However, certain periods are not predicted well. Furthermore, even though the general trend is captured, some deviations are apparent when assessing performance on a day-to-day basis. Given the general character of the atmospheric classification at both local and synoptic scales, it is not surprising that some special situations are not predicted well. Information on local air mass characteristics is limited to temperature

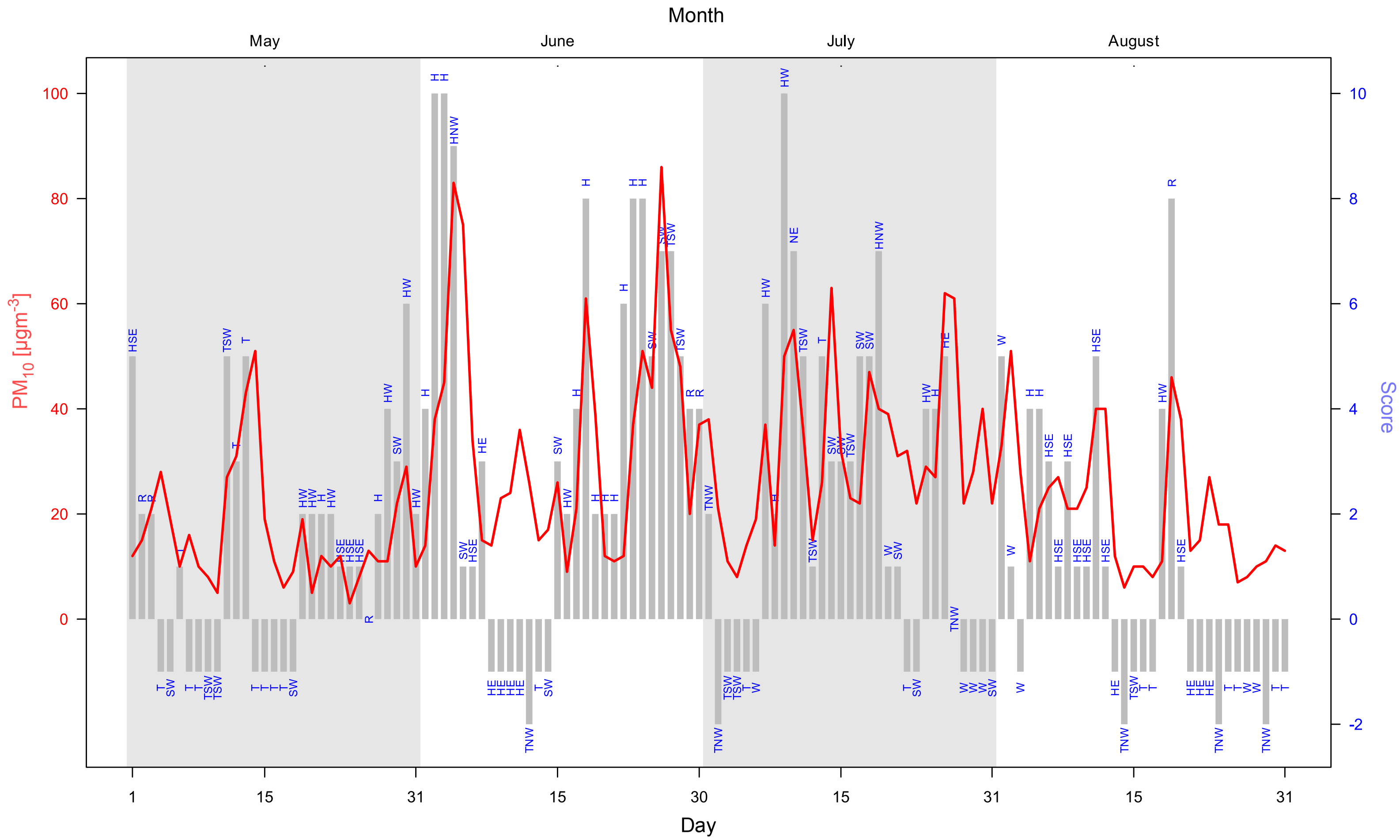

Figure 6.1: Comparison of predicted meteorological pollution potential (Score - grey bars) and observed PM_{10} concentrations (red line) in winter 2009. Synoptic type classification for each day is given in the plot at each daily score level (blue). An explanation of score values is provided in the text and in Table 6.1.

and wind speed. Furthermore, as outlined earlier, day-to-day variation in concentrations is not only a function of meteorological variability, but also influenced by socio-economically driven variations in emission release. Additionally, air mass stability is not accounted for in EPIC, which might improve prediction performance, at least slightly.

The synoptic circulation influences dynamic airflow modification in relation to changes in surface characteristics. In New Zealand, the most dominant surface features that frequently modify gradient flow are the Southern Alps. For the Canterbury region, this modification is strongest for synoptic conditions that promote flow from westerly quadrants, as it is then situated on the lee side of the Southern Alps. Sturman & Tapper (2006) gave an in-depth description of orographic flow modification along with various examples from New Zealand. They noted that north-westerly gradient flow produces a great range of atmospheric characteristics in the lee of the Southern Alps, "... which are created by the variability in wind speed, atmospheric stability, and moisture distribution in the air moving across the mountains (Sturman & Tapper 2006, p. 290)." Therefore, it can be expected that for situations of westerly to north-westerly flow, the classification may not provide an accurate assessment of pollution potential due to enhanced mesoscale orographic flow modification. It is in fact true that all periods that show bad prediction skill are periods of either westerly or north-westerly gradient winds when orographical modification of the gradient flow is high. As a result, mesoscale flow characteristics become the dominant factor that influences local atmospheric conditions, and the link between local and synoptic conditions becomes less clear, as outlined in Section 2.2. For example, during the period 8 - 12 June 2009, an increase in PM_{10} concentrations is observed even though pollution potential is expected to be low. Gradient flow during this period is northwest (HE), which is truly perpendicular to the alpine barrier. Additionally, given the north-westerly gradient flow, the observed increase in PM_{10} levels during this period may also result from dust advection, either as a result of long range transport of Australian desert material as shown in Collyer et al. (1984), or, more locally, due to dry and gusty foehn winds as described by McGowan (1997). This, however, should be easily detectable, as the diurnal pattern of concentrations is likely to be different from the pattern observed as a result of domestic fire emissions. However, at the time of investigation, only daily averages were available. The hourly recordings were still subject to the data quality assurance procedure that ECan applies to all high frequency measurements.

On a local scale, atmospheric stability influences dispersion by allowing or restricting vertical air movement. Especially at night, when the surface energy budget turns negative and radiative heat loss becomes the dominant flux component, surface inversions can form and create stable conditions that cause pollutants to be trapped close to the surface (Oke 1987). In Christchurch, local atmospheric stability is still a key factor that influences pollution dispersal. However, it has been shown in Section 3.2.3 that it may not be a useful predictor for pollution concentrations, due to the fact that under worst conditions, stability may be less than under less severe conditions.

To assess the performance of the pollution potential classification in a quantitative way, one-way ANOVA between PM concentrations and the EPIC scores was performed. Note that, PM levels were log-transformed to approximate a normal distribution. The results of the ANOVA are shown in Table 6.2 and outline that the different score levels significantly reduce the sums of squares of PM observations and hence can be understood as a good representation of expected PM concentrations.

Table 6.2: Summary of one-way ANOVA between EPIC scores and PM_{10} concentrations in winter 2009.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Score	1	14.55	14.55	43.04	0.0000
Residuals	121	40.91	0.34		

In conclusion, the presented exceedence probability index EPIC is based on a two dimensional representation of atmospheric processes as no information on vertical atmospheric stratification is incorporated. Furthermore, even though it accounts for processes on synoptic and local scales, it lacks information of mesoscale processes. In spite of this, EPIC index is seen to estimate general concentration patterns rather well, which is very encouraging. However, information on vertical atmospheric structure may enhance the performance of the predictions and should be integrated if this approach was ever to be implemented as an automated pollution forecast system for Christchurch. Furthermore, given that the performance is particularly bad under westerly to north-westerly gradient flow situations, information on air mass characteristics from an upstream location of the Southern Alps may increase prediction accuracy. The location for this should be some distance offshore in the Tasman Sea to ensure assessment of air mass characteristics that are not yet modified by the New Zealand orography.

Chapter 7

Discussion and conclusions

In this thesis, atmospheric controls of PM_{10} pollution and associated trends have been analysed quantitatively and qualitatively across a variety of spatial and temporal scales. The core analysis of this research resolved around a classification tree approach, which produced flexibly applicable pollution probability classes, that laid the foundation for subsequent analyses. A major focus of this thesis was the comprehensive quantitative analysis that tied together a number of statistical approaches in a unique way to enable the investigation of atmospheric influences on local air quality in Christchurch across a wide range of scales. The main findings of this thesis with regard to the primary research objectives are summarised below (sections in which these findings can be found are given in square brackets where appropriate), followed by a discussion on implications and perspectives of the findings and recommendations for future research in both a national and international context. The three primary research objectives that this research has addressed are:

- to investigate the nature of trends in particulate pollution in Christchurch on annual to decadal scales,
- to quantify particulate pollution potential for varying atmospheric conditions in a Southern Hemispheric mid-latitude setting, and

- to identify local, synoptic and climatological mechanisms that control particulate pollution potential in an environment dominated by smoke from domestic fires.

7.1 Summary of main findings

I. Investigation of the nature of trends in particulate pollution in Christchurch on annual to decadal scales

- Approaches used in previous studies in the international literature for assessing meteorologically adjusted pollution trends needed to be modified to allow for non-constant emission release, as domestic fires are the dominant source in Christchurch. [Section 3.3]
- Two different statistical approaches, (a) a regression approach based on continuous measurements of PM_{10} concentrations and (b) a classification tree approach using daily exceedence statistics, both revealed a downward trend in PM_{10} concentrations over the last decade, when local meteorological variability is mostly accounted for. [Section 3.2.4 & 3.3]
- On an interdecadal scale, a clear periodicity in atmospheric conditions that are likely to promote elevated particulate levels, has been found. This periodicity has a frequency of approximately 16 years. [Section 5.2.2]

II. Quantification of pollution potential for varying local atmospheric conditions in a Southern Hemispheric mid-latitude setting

- Through classification tree analysis, five exceedence probability classes were identified that show varying potential to degrade air quality in Christchurch. Probabilities of national air quality guideline exceedence range from 0.04 to 0.82, depending on the combination of the minimum temperature of the following day, the average wind speed between 1200 hrs and 2400 hrs, and the average wind speed between 1800 hrs and 2400 hrs. High pollution days generally show decreased wind speeds during the afternoon and especially after 1800 hrs, along with thermal conditions around or below 0 °C the next morning. [Section 3.2.2]

- An alternative classification tree analysis, utilising a more comprehensive set of meteorological predictor variables sampled at higher frequencies, did not yield major enhancements of the pollution classification. [Appendix A]

- An index derived from the combination of both a local atmospheric pollution potential classification and its relation to synoptic conditions provided encouraging short-term pollution prediction potential and was found to be significantly correlated to observed PM_{10} concentrations. Even though lacking accuracy in capturing day-to-day variation in concentrations, the general trend is predicted very well. [Chapter 6]

III. Identification of regional, synoptic and climatological mechanisms that control particulate pollution potential in an environment dominated by smoke from domestic fires

- The main processes on a local to regional scale that govern pollution dispersion in Christchurch are flow stagnation and recirculation associated with a nocturnal flow transition between day-time north-easterly winds and night-time westerlies. The timing of this transition is crucial. If this transition occurs shortly after the time of peak emission release, associated flow stagnation and recirculation of particulates exacerbate the situation severely and the worst air quality conditions are found under these conditions. A later occurrence of this transition generally allows for quicker dispersion and reduced recirculation. [Section 3.2.3 & Chapter 4]

- Synoptic conditions that produce elevated levels of particulate matter in Christchurch are generally characterised by high pressure systems located in close vicinity to the west of the country or over the (eastern)

South Island, which favour nocturnal decoupling of the lower atmosphere from flow aloft for the outlined transition process to take effect. [Section 5.1]

- Synoptic flow from northerly quadrants, along with zonal flow over the South Island can be considered as most favourable for good air quality in Christchurch. [Section 5.1]

- South-westerly flow conditions and anticyclones located to the east of the country may result in both good and bad air quality. [Section 5.1]

- Air quality in Christchurch shows a clear relation to synoptic transition patterns that result from anticyclones, that are embedded in the mid-latitude westerlies, which regularly cross the country during their eastward propagation. The realisation of this anticyclonic passage is subject to latitudinal variation, which influences the duration of synoptic conditions that are conducive to degraded air quality in Christchurch. A pathway to the north of New Zealand is generally most favourable for good air quality, a central anticyclonic passage (over the northern or central part of the country) marks the worst case, whereas a southern pathway can be considered as intermediate. [Section 5.1]

- Inter-decadal variability in pollution potential is influenced by variations in the winter time intensity of the Southern Annular Mode, that exhibits a periodic signal with a wavelength of approximately 4 - 6 years. [Section 5.2.2]

7.2 General and future implications of the main findings

Analysis of medium-term trends (10 years) has been carried out using two different statistical approaches. A regression based approach with subsequent filtering to reveal the low frequency longer term trend, which had produced good results in previous international studies, needed to be revised to allow for non-constant, seasonal particulate emission release in Christchurch. Ambient temperature was used as a proxy for seasonality. An adjustment of concentrations between high and low emission seasons based on simple trigonometric recalculation of deviations from expected (predicted) concentrations enabled comparability of concentrations between seasons. This then allowed for removal of variability in dispersion rates due to variations in atmospheric conditions and, ultimately, the detection of a low frequency (longer term) trend that appears to match changes in emission release over the last decade. The second approach was based on classification tree analysis, that classified ambient atmospheric conditions with regard to number of exceedences of the national air quality guideline. This enabled assessment of PM_{10} concentrations over time within a fixed frame of meteorological conditions for a number of different pollution probability classes. Fundamentally, both approaches follow the same principle of assessing temporal trends in PM_{10} concentrations after some measure has been taken to assure that meteorological variation within the analysed time series is kept to a minimum. Both analyses yield a decreasing trend in the amount of particulates, that occur each winter, over the last decade in Christchurch (at least at Coles Place) and thus provide solid evidence that local policy measures that have been implied in recent years start showing the desired effect. It is hard to say which of the approaches produced the more solid or more accurate results, as comparison between the two methods is difficult. However, the results of both approaches are consistent. No attempt has been made to quantify the observed decrease in PM_{10} concentrations, as remaining year-to-year variability is high and therefore, quantification of the trend would be of weak significance.

With regard to implications for local environmental authorities, this might seem somewhat disappointing, as no direct quantification of the success can be provided. However, the fact that all trends that were identified are either statistically significant (Section 3.2.4) or well in line with previous findings (such as Scarrott et al. 2009 - Section 3.3), does provide a quantitative evaluation of the efforts taken by the authorities, even though in a more general sense. The two approaches differ quite substantially with regard to required data preparation, with the regression based approach being much more demanding in this respect. Additionally, with regard to the interpretation of the respective outcomes, the classification tree approach is much more user-friendly. Furthermore, as will be discussed in later paragraphs, the results of this analysis are much more flexible and proved universally applicable to a variety of other investigations. Therefore, for the purpose of ongoing monitoring of the trend, the identified classification may be used to continue the evaluation of ambient particulate levels in the future. This is easily achieved by classifying each day between May - August at the end of each winter accordingly and subsequently assessing percentile and median concentrations for each class. This will provide a straightforward extension to the findings presented here, and will help to gain further confidence in them.

In the light of the identified periodic nature of the occurrence of synoptic conditions that are likely to reduce air quality in Christchurch, a continuing trend assessment will be even more useful. It will be interesting to see the development of pollution levels with regard to varying climatological influences, especially as it is suggested that a period of increased frequency of winters that show greater potential for degrading air quality, can be expected at some stage during the next decade. With regard to the regression approach, it may be more feasible to repeat such analysis at greater time intervals, due to the mentioned significant requirements of data preparation and manipulation.

Having a classification that is able to assign an exceedence probability to any given day based on local meteorological conditions, provides a tool that can prove useful for a variety of applications. Apart from its utilisation for trend assessment that was discussed earlier, it allows for basic short-term pollution forecasting. Given that the classification has been successfully tested (Chapter 6) and that it has been shown that a more complex approach did not yield significant enhancements, confidence in the presented classification is high. It can give a straightforward and quick quantification of expected air quality for any given day that the required atmospheric parameters are known. The value of this lies in its ease of applicability. Sufficiently accurate weather forecasts for a period of up to a few days are nowadays readily available, so that an instantaneous assessment of expected pollution levels is possible through the exceedence probability classification. The incorporation of synoptic type classification, as has been done in Chapter 6, is somewhat difficult to implement in an automated fashion, as these would need to be part of the utilised weather forecast. Plans are underway to provide such synoptic type classification as part of an automated weather forecasting system implemented at the Centre for Atmospheric Research at the University of Canterbury.

Despite the fact that a quick and easy quantification of expected air quality can be provided based on the findings of this research, any attempts to develop a fully automated pollution forecast for Christchurch would need to extend the approach taken here in several ways.

- Firstly, incorporated observations from which to derive exceedence probabilities should be extended spatially, so that atmospheric conditions from additional sites are incorporated. This might enhance the prediction accuracy by providing information on spatial and temporal evolution of governing processes that have been shown to play an important role in controlling the dispersion potential of the Christchurch urban atmosphere. This is especially important with regard to the identified transition meteorology and related dispersion processes. Spatially extended information on atmospheric conditions, especially towards the foothills of the Southern Alps, may give an indication of the expected arrival of the alpine drainage current, and may thereby provide an approximation of expected dispersion strength, which is likely to enhance forecasting ability.

- Secondly, even though no clear relationship has been found between low level atmospheric stability and pollution concentrations, vertical atmospheric information from spatially distributed stations may enhance predictions, as the quality of atmospheric representation in the forecasting system will be increased. Additionally, extended information on the complex three dimensional wind field should enhance the general understanding of dispersion meteorology for the region.

- Thirdly, and most importantly, the incorporation of pollution levels from past days is expected to greatly enhance prediction performance, as potential residual particulates from earlier pollution events, that may be re-circulated, are expected to have great influence on measured concentrations. Incorporation of concentrations of preceding days is standard practice in pollution forecasting systems around the world, and therefore, should also be considered in the case of Christchurch.

In general, the fact that this research has identified meteorological conditions during the evening to be most influential for pollution build up and the occurrence of exceedences, provides further evidence that any future regulatory measures should be focussed on emission release during this period.

The mechanisms of pollution dispersion that were found in this research, namely flow transition and associated surface flow features, have been previously identified to be important low level flow processes in the international literature through laboratory experiments, numerical simulations and observations for various locations around the world. However, most of these studies focussed on areas that are located within or in the close vicinity of complex topographical features such as mountain valleys or basins. With regard to the Southern Alps, Christchurch is separated by quite some distance over the Canterbury Plains from the topographical features where air masses are formed that directly influence the day-to-day dispersion potential of its urban atmosphere. Therefore, this research adds to the general understanding of meso-scale meteorology, by providing a case study that delivers evidence that terrain-induced features can be highly influential with regard to pollution dispersion, even in urban areas that are located some distance away from the place of formation of the contributing low level flow features. The fact that the mechanism of flow transition and associated flow stagnation and recirculation has been identified through both measurements and also a numerical modelling exercise, highlights the importance of this mechanism for the Christchurch urban area.

The mentioned numerical simulation of the transition process was carried out in a novel approach, using climatological average wind field observations to assimilate different low level flow regimes into a synoptically autonomous model domain to gain a deeper understanding of temporal and spatial variations of the identified mechanisms. Such a numerical technique has not been reported in the international literature so far. This numerical investigation was able to reproduce differences seen in pollution measurements quite accurately, which highlights its potential in being applied more widely in other locations. This said, there is great potential in refining the method used here, by, for example, assimilating varying average atmospheric initialisation profiles for different case investigations that cover the complete vertical extent of the domain. Such profiles could be derived from re-analysis data sets for example. Either way, although this approach has proven to be very useful in this research, there is great need for wider application to evaluate its general usefulness for a variety of research scenarios.

Investigation of synoptic controls on reduced air quality in Christchurch identified anticyclonic situations with a centre located close to the region of interest to be most influential. This is certainly not surprising and has been reported repeatedly in the international literature for some time. From a national and local perspective, however, the investigation is of higher value, as it quantifies synoptic controls, their average persistence and transitional patterns with local air quality in a causal relationship, especially when combined with local meteorological conditions, so that given scenarios can be directly related to expected exceedence potential. As a result of the nature of this research, investigation of synoptic controls is of general character and lacks examination of synoptic variability and its relation to associated modification of the mesoscale flow field. Therefore, future research should be aimed more towards understanding the great variety of local atmospheric conditions that is apparent under similar synoptic conditions and try to identify mechanisms (most likely on a mesoscale) that produce such variety. This may shed further light on the high variability in PM_{10} concentrations under seemingly similar atmospheric characteristics. In fact, even though the general approach taken in this study, was able to explain a significant amount of the observed variations in air quality in Christchurch, there is still a substantial amount of variability that cannot be explained by the results found here. Some of this residual variation will result from fluctuations in the socio-economical factors that influence anthropogenic emissions, but it is expected that a portion of the remaining variability may be explained by further in-depth analysis of regional mesoscale meteorological variations.

Inter-decadal variation in meteorologically controlled air pollution potential shows a distinct periodic fluctuation in synoptic conditions which are likely to degrade air quality in Christchurch. Apart from a qualitative assessment of possible forcings, which revealed a close phase relationship of the observed periodic signal with variations in the winter time intensity of the Southern Annular Mode, no further analysis into possible hemispheric to global atmospheric influences on local air quality has been carried out. Hence, there remains huge uncertainty, which, at the same time, provides great potential for future research in this area. Climatic variation and associated hemispheric to global forcing mechanisms have been the focus of many studies worldwide. Most of these, however, focus on influences on the resulting climatic conditions themselves or the investigation of extreme events such as floods or droughts. Long-term climatic investigations from an air quality perspective are much less common, mostly due to the restricted time span of available measurements. The proxy based approach to extend the period of analysis used in this research provided promising preliminary results, and should be pursued further.

From a regulatory point of view, the identified historic variation in pollution potential in Christchurch allows recent air quality monitoring, especially the identified medium-term trend, to be put into a wider perspective. It reveals that, even though PM_{10} concentrations have been decreasing in recent years, it is likely that general conditions that favour degraded air quality may (again) become more frequent in the near future, as they have been repeatedly in the past, such as during the late 1990s.

With exception of a brief description of projected frequency changes of synoptic conditions at the end of the 21st century, all of the identified atmospheric influences and mechanisms that control the likelihood of degraded air quality in Christchurch presented in this study, are the result of analyses that have not taken into account any potential underlying general global warming trend, and may be biased in this respect. However, the comprehensive investigation of atmospheric influences on a variety of scales, should enable good inference of any such influence on Christchurch's air quality climatology, if/when detected.

Philosophical reflection

Besides the intention to provide useful and valuable answers to the formulated research questions which will hopefully provide support for local authorities and their (future) policy decisions, this thesis also addresses a number of more fundamental aspects of the air pollution problem in Christchurch (which is a more sound basis for the award of the title 'Doctor of Philosophy'). So far, however, this thesis does not adhere to any philosophical component. Therefore, in this final section, I would like to devote some thinking to the broader philosophical realm of this thesis. This is by no means an all-embracing reflection of philosophical implications that surround this research (if that is even possible), it is rather an excursion into the dilemma of logical reasoning behind some aspects of the methodology that was used in this research. The intent of this is to widen the horizon of the fundamental meaning and to explore different pathways of interpretation of the presented results that lies beyond the scientific reality of empiricism.

The main scientific approach taken in this study is based on formulating probabilities or likelihoods of the realisation of certain events. Of course, processes that influence these events have been investigated and aided the understanding and helped rationalise the differences between certain events. However, the core line of argument of this thesis resolves around expressions such as 'probability', 'likelihood', 'potential' or more general wordings like 'expected'. There is a fundamental dilemma when using such expressions. They are easy to comprehend and convey a sense of quantitative value. However, they are, fundamentally, not a good representation of reality, apart from the field of Quantum Mechanics (which deals with a different kind of probability all-together).

At a fundamental level, what exactly is probability and how is it determined? In a way, it is the quantification of knowledge that is acquired through experience. An example should clarify this. When one puts their hand on the element of the kitchen stove for the first time, there is no conception of possible consequences, as no prior experience exists that one could base such conception on. Independent of the experience, the causal association that is made is pure and absolute. The hand on the stove either causes pain, or it doesn't. With repeated encounters between hand and stove, the association becomes less clear, as sometimes the element will be cold, sometimes it will be hot. Over time, more complex conditional relationships may emerge, as one recognises that, when mum has just finished cooking that delicious custard, the element is hot without exception. Ultimately, this leads to the establishment of a concept of probability that helps quantify the expected results of the action: "if I put my hand on the stove element, chances are it will be painful, especially when mum has just finished cooking that delicious custard." Thus, probability is a complex concept of the quantification of experience. This is also true for this thesis, as it quantifies the expected outcome of whether the national air quality guideline will be exceeded or not, given a certain atmospheric set-up. The set of experiences, in this case, are the various realisations of atmospheric conditions, as described by a collection of certain combinations of meteorological parameters. And the formulated probabilities, in particular those resulting from the classification tree analysis, are the conditional conception of the likely (exceedence) outcomes for a given (atmospheric) scenario.

From an analytical point of view it is valuable to know that, given the current state of the atmosphere, an exceedence of the national air quality guideline will happen with a likelihood of e.g. 86%, as it allows conclusions about the importance of the atmospheric status with regard to air quality (which has been comprehensively investigated and discussed in this thesis). But in terms of the actual present or future realisation of an event, this number is rather useless, as an exceedence either occurs or not. A probability of 0.86 may be a statistically correct representation of a real event, but one faces the dilemma of how to interpret and use this information.

To grasp this dilemma, let us assume the position of a pollution forecaster. In this case, one needs to decide whether to forecast an exceedence or not, hence one is faced with an 'either/or' or binary decision. As shown earlier, decisions are generally taken based on experience (the clear relationship between the hot stove element and the mother's cooking will lead to the decision not to place the hand on the element). In this case, the experience is, that in 86 out of 100 cases with similar atmospheric conditions, the guideline has been exceeded in the past. But what does this mean for the one case that is to be forecast? If the realisation of an exceedence lies between the extremes of no exceedence (0) and exceedence (1), does this then mean that 0.86 of the exceedence will occur? Most 'likely' not. But what does this imply then? What is the actual value of this number? And how does a value of 0.86 relate to, e.g. a value of 0.12? If they are both not a representation of possible realisations of the event in the real world, then what do they represent? To understand one of the meanings that these numbers have, let us again put ourselves in the position of the pollution forecaster. For the forecaster, the person deciding between 0 and 1, these numbers would relate to the confidence with which a decision is made. Assuming that nobody likes to be proven wrong, then these values provide a level of security for the forecaster to take the correct decision. In the case of 0.86 it is safer to predict an exceedence and for a probability of 0.12 it is safer not to. So, in the case of pollution forecasting, a probability of 0.86 (0.12) does not actually represent the likelihood of an exceedence to occur, it rather represents the likelihood of a forecaster to take the decision to predict one (or not to).

The intention of this brief example is to highlight the plurality of possible interpretations of conclusive scientific reasoning. By no means do I claim that this section adds any deeper scientific or philosophic value to this study, but I can honestly say that I thoroughly enjoyed this brief excursion into alternate ways of reflecting upon the fundamental meaning of the findings of this research.

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Appendix A

Alternative classification tree analysis

In Chapter 3.2, classification tree analysis was used to classify local meteorology with regard to its influence on air quality. The binary response whether the current air quality guideline is breached or not was regressed against a set of meteorological predictor variables (Table 3.1). This produced five exceedence probability classes which were shown to be associated with distinct synoptic control mechanisms (Section 5.1). Due to issues relating to missing observations, assessment of historic exceedence potential was not possible (Section 5.2). Therefore, classification tree analysis was repeated with more comprehensive temperature information at higher temporal resolution plus information on vertical atmospheric thermal stratification. This is expected to enhance statistical power of the set of predictors and hence produce a better classification in terms of class purity and also with respect to capturing underlying physical processes. A discussion on the comparison between the original classification and the one incorporating the extended temperature information is given in this appendix.

Table A.1: Extended list of predictor variables for alternative classification tree analysis.

Variable name	Description [measurement unit]
Tmin_i1	Minimum temperature of the following day [°C]
Tmax_i_Tmin_i1	Difference between maximum temperature of considered day and minimum temperature of following day [K]
ws_00_06	Mean wind speed between 0000 hrs and 0600 hrs [m/s]
ws_06_12	Mean wind speed between 0600 hrs and 1200 hrs [m/s]
ws_12_18	Mean wind speed between 1200 hrs and 1800 hrs [m/s]
ws_18_24	Mean wind speed between 1800 hrs and 2400 hrs [m/s]
ws_00_12	Mean wind speed between 0000 hrs and 1200 hrs [m/s]
ws_12_24	Mean wind speed between 1200 hrs and 2400 hrs [m/s]
ws_18i-1_24i-1	Mean wind speed between 1800 hrs and 2400 hrs of preceding day [m/s]
ws_18i-1_06	Mean wind speed between 1800 hrs of preceding day and 0600 hrs of considered day [m/s]
rh	Relative humidity at 0900 hrs [%]
p	Mean sea-level pressure at 0900 hrs [hPa]
p_i-1_i	Difference in mean sea-level pressure at 0900 hrs between preceding day and considered day [hPa]
rad	Daily global radiation [MJ]
rain	Accumulated 24h rain [mm]
	additional temperature information
T_00_06	*Mean temperature between 0000 hrs and 0600 hrs [°C]*
T_06_12	*Mean temperature between 0600 hrs and 1200 hrs [°C]*
T_12_18	*Mean temperature between 1200 hrs and 1800 hrs [°C]*
T_18_24	*Mean temperature between 1800 hrs and 2400 hrs [°C]*
T_00_12	*Mean temperature between 0000 hrs and 1200 hrs [°C]*
T_12_24	*Mean temperature between 1200 hrs and 2400 hrs [°C]*
T_18i-1_24i-1	*Mean temperature between 1800 hrs and 2400 hrs of preceding day [°C]*
T_18i-1_06i	*Mean temperature between 1800 hrs of preceding day and 0600 hrs of considered day [°C]*
T_18i_06i+1	*Mean temperature between 1800 hrs of considered day and 0600 hrs of following day [°C]*
T_06i+1	*Temperature at 0600 hrs of following day [°C]*
T_18i_06i+1	*Temperature difference between 1800 hrs of considered day and 0600 hrs of following day [°C]*
∆T_18i_24i	*Mean vertical temperature difference between 1800 hrs and 2400 hrs of considered day [K]*
∆Tmax_18i_06i+1	*Maximum vertical temperature difference between 1800 hrs of considered day and 2400 hrs of following day [K]*

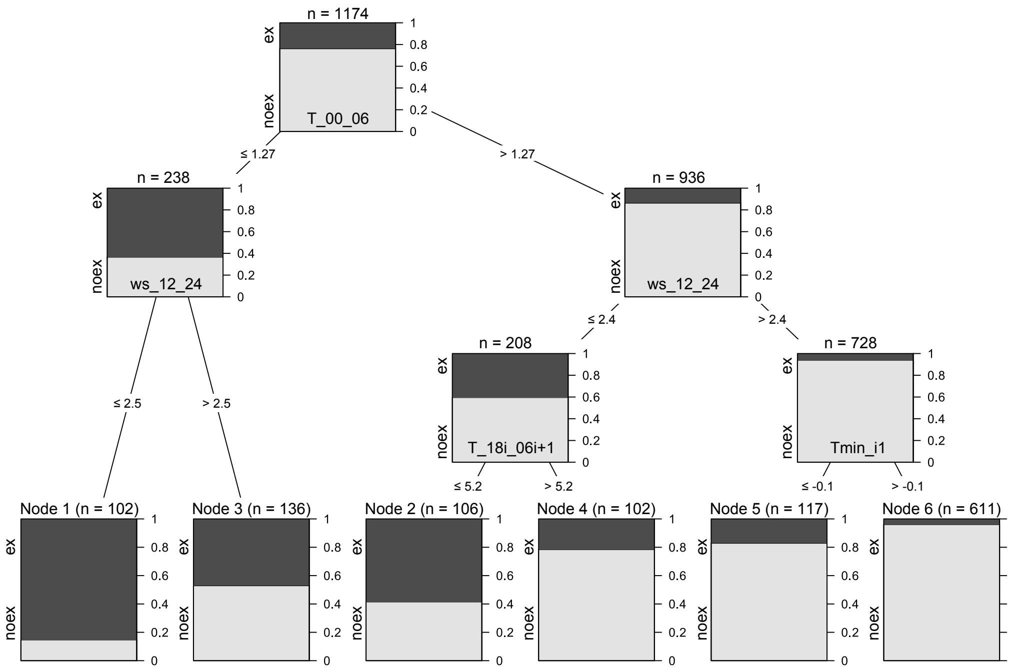

Figure A.1: Classification tree based on extended set of predictor variables.

Figure 3.1 shows the original exceedence probability classification as based on the predictors outlined in Table 3.1. For the alternative classification tree analysis, additional temperature information based on averages derived from hourly observations as well as information on vertical temperature gradients was used. Table A.1 shows these listed in italics along with the variables used for the original classification run. This alternative set of covariates lead to a classification tree that shows some deviation, though is not completely different from the original. Figure A.1 denotes the new tree with six terminal nodes (in comparison to five in the original tree). There are still three split levels, although, two of the newly introduced predictors are now used to derive this classification *(T_00_06 & T_18i_06i+1)*. In line with precious findings in this thesis, vertical temperature information did not yield enhanced predictive power and was not utilised during the recursive partitioning.

In terms of terminal node purity of the highest and lowest pollution probability classes (0.853; 0.039 respectively), no major improvement can be seen. Exceedence probabilities in these nodes from either end of the spectrum are fairly similar to those found in the original analysis (0.824; 0.043). Additionally, the respective prediction performance of both classifications is very similar, as can be seen in Table A.2. Cross-tabulations of predicted versus observed exceedences do not yield major differences in the amount of mis-classifications either way, which indicates that both classifications show similar performance, although the original classification tree predicts a few more exceedences than the alternative one.

Table A.2: Comparison of predicted versus observed exceedences for both classification tree scenarios. 'Obs' = observations, 'Pred' = predictions, 'ex' = exceedence, 'noex' = non-exceedence day.

Original			Alternative		
Pred	**Obs**		**Pred**	**Obs**	
	ex	*noex*		*ex*	*noex*
ex	**152**	**61**	*ex*	**149**	**59**
noex	**127**	**834**	*noex*	**130**	**836**

Apart from the incorporation of additional temperature information, the set up of the CART algorithm was identical. For ease of reading, the following paragraph provides a copy of the description of the algorithm that was given in Section 3.2.2. A more detailed examination of the underlying statistics is given thereafter. For a complete description of the recursive partitioning algorithm used in this study, refer to Hothorn et al. (2006).

"Based on a set of predictor variables, this statistical approach uses recursive partitioning to split the response into a set of classes (nodes) with maximum class purity and arranges the final splits into a decision tree diagram. At each stage of the partitioning, all possible splits are identified using a Monte Carlo approach. For each potential split a p-value is calculated using a suitable statistic (depending on the nature, notably the statistical scale, of the predictor variable) to ensure comparability of the split criteria. Finally, a split is made to produce exactly two nodes using the predictor with the lowest p-value. Each of these nodes then becomes the input and the procedure is repeated as outlined above. In order to avoid over-fitting of the classification tree, it is possible to control for minimum node size, i.e. the minimum amount of observations the resultant nodes must have after each split. Furthermore, the p-value for possible splits can be specified so that splits are only allowed if the split-statistic is significant at a p-value lower than the specified level."

The aim of the in-depth comparison of the two classification trees described in this appendix is to investigate the split-statistics that lead to the outlined classifications in more detail. As *Tmin_i1* was used in the original set up to approximate thermal conditions during early morning hours of the next day, it is encouraging to see that the introduction of higher resolution temperature information still identifies early morning hours *(T_00_06)* as the most influential period with regard to exceedence probability. This outlines the importance of atmospheric conditions during this time of day and provides further confidence that the analysis is indeed capturing relevant processes leading to air pollution events. However, there is a significant difference with respect to the timing of the identified process. Conditions represented by *Tmin_i1* denote atmospheric influences after the event, whereas *T_00_06* represents ambient conditions at the beginning of it. In the light of this, the latter variable may simply be a representation of a pollution event immediately prior to the one under investigation, hence indicating residual particulate concentrations from the preceding day that are influencing air quality of the day in question. From a meteorological point of view, atmospheric persistence becomes important, as two subsequent days can certainly not be considered as separate. The state of the atmosphere at any point in time is always a result of autocorrelation effects of prior, constantly evolving physical states (as described e.g. by Brett & Tuller 1991). Therefore, the regulatory time period definition of an exceedence event will always represent a limitation to accurate meteorological assessments, which results from atmospheric processes with no sharp temporal limits.

To further investigate and compare the performance of both classifications and potentially decide which of these is more robust, it is necessary to examine the split-statistics that lead to the respective decision trees. A quantitative comparison of these provides insight into the statistical process that underlies the analysis and may help to assess which analysis is likely to be more representative of real-world processes leading to exceedences. Hothorn et al. (2006) described the procedure of the partitioning in general terms to be a three step process:

1. Test whether a significant dependence between any of the predictors and the response can be found, and if so, select the covariate with the strongest association. If no significant relationship can be established, stop the algorithm.

2. Within the vector of the selected covariate, establish a conditional distribution of all possible realisations of the response at given levels (or intervals of continuous values) of the predictor, based on a specified amount of random sub samples from the considered covariate population. The split is established at the predictor level (value) that yields the most significant difference in the conditional distribution as compared to the global covariate distribution.

3. Steps 1 and 2 are repeated within each resulting node with adjusted populations, until no further significant dependence can be found, or until the minimum number of node observations is reached.

Furthermore, Hothorn et al. (2006) stated that the utilisation of linear statistics in the permutation test framework enables standardisation of the test statistics, so that examination of established splits is straightforward. Figure A.2 shows these standardised statistics (S) as scatterplots against the respective split variable for each node of the original and the extended classification tree analysis. Standardisation enables direct comparison of statistical power of each split, not only within each tree but also across trees. To evaluate the goodness of each classification and compare these, the primary splits that are implemented in each tree need to be examined. Across-tree examination of split statistics for the remaining inner nodes is not feasible as their respective populations are likely to be different. When assessing the goodness of these primary splits, the two characteristics that are of importance are (a) the absolute magnitude of S (i.e. the maximum value) which represents the power of the implemented split, and (b) the cleanliness of the split (i.e. whether a single and clear maximum in S can be found). With regard to (a), statistical power of both primary splits is very similar. Covariate *T_00i_06i*, the covariate used for the primary split in the alternative classification, yields S = 16.10, which is only marginally higher than that of *Tmin_i1* with S = 15.54. In addition to this, the primary split of the original classification can be considered to be more robust as S for *Tmin_1* shows a distinct peak indicating a clean split. A realisation of the primary split of the extended classification on the other hand, would generally have been possible anywhere between the identified split value of covariate *T_00i_06i* at 1.27 °C and a much larger value of around 4 °C, indicated by the very similar values of the split statistic in this range. A further argument for the robustness of the primary split of the original classification is provided by the fact that the same split is realised as the final split in the alternative classification, hence indicating universal explanatory power.

Split statistics for the remaining nodes paint a similar picture. Splits identified in the original classification seem to be clearer than those for the alternative classification, though not necessarily of higher statistical power. For *ws_12_24*, a value of 2.4 [m/s] is identified in both cases for split realisation (second split level of low pollution branch in both classifications), again

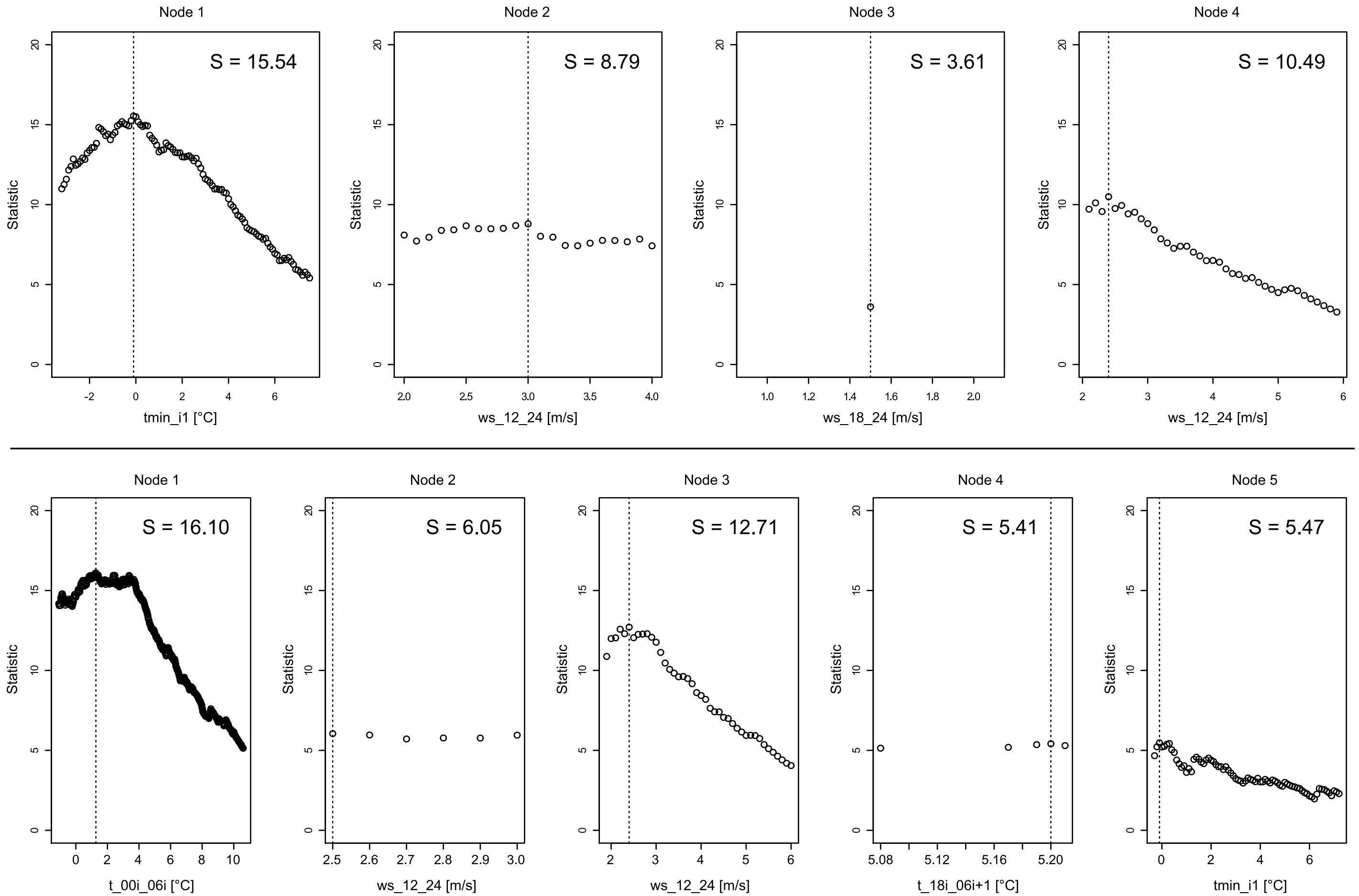

Figure A.2: Scatterplots of standardised statistic and identified split predictor variable for each inner node of the original classification tree (upper panel) and the extended classification tree (lower panel). Maximum values for standardised statistic S are shown for each split.

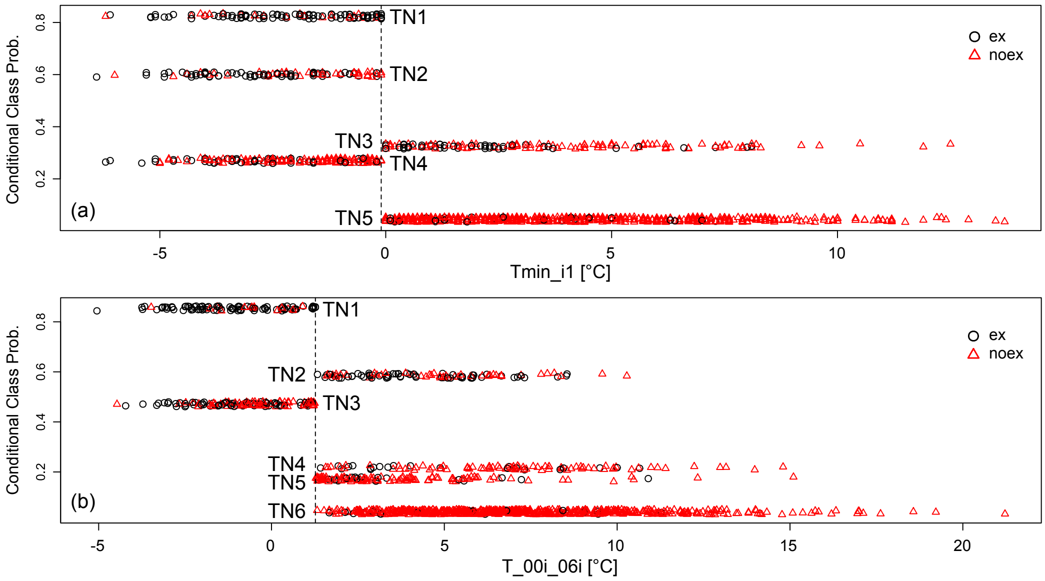

Figure A.3: Conditional class probabilities as a result of the primary split for (a) the original classification and (b) the extended classification.

indicating a robust universal measure of pollution potential. The second split level of the high pollution potential branch, however, sees two different realisations of the same split variable *(ws_12_24)* in the two trees. At a closer look at the split statistics, it becomes clear that the realisation of this split in the extended classification at 2.5 m/s could essentially have been done anywhere in the range between 2.5 m/s and 3 m/s, thus be identical to the corresponding split in the original classification at 3 m/s.

Finally, a look at the conditional class probabilities that result from the primary split in each classification (Figure A.3), reveals that the profound difference between the two cases is of procedual character. The primary split of the original classification seems to favour the isolation of a maximum of exceedences (black circles), whereas for the extended classification the isolation of a maximum of non-exceedence days (red triangles) seems to be the focus of split one. This certainly highlights the complexity of the classifications tree analysis in general and shows that comparisons are difficult.

Nonetheless, the presented in-depth examination of the underlying statistics that lead to the two different exceedence probability classifications, provided valuable information on the robustness of the two cases. In summary, due to the identified characteristics of split cleanliness and statistical power behind the splits, the original classification seems to be more robust and hence, seems to be a better representation of real-world processes. This leads to the conclusion that the incorporation of both higher resolution and vertical temperature information does not increase the goodness of the probability classification. In fact, it leads to a classification that is less robust. Any future attempt to incorporate additional information into the classification tree analysis with regard to exceedence probabilities (such as air quality measurements of previous nights to potentially enhance predictions), should be assessed at the same level of detail as presented in this appendix, as the underlying statistics certainly aid interpretation of robustness, power and hence the potential of capturing and representing real-world processes.

Appendix B

Climate data quality

Below is an excerpt of a conversation with NIWA, the national institution that maintains "CliFlo: NIWA's National Climate Database on the Web" (CliFlo), the national database for meteorological and climatological data. This inquiry was ignited through some suspicious observations found at another station near Christchurch airport, at Lincoln.

"Hello, I am a frequent user of your database. [...] I am very suspicious about your hourly wind recordings in general. The meta data defines wind directions that are recorded as zero to be calm (i.e. not missing), but I simply cannot believe that Lincoln (Canterbury) should have experienced approx. 10 days of continuous calms between 07/07/2000 1000 hrs and 17/07/2000 1200 hrs. Could I please get clarification [...]. Thanks, Tim."

"Dear Tim, I have checked with our Instrument Systems and the period in July 2000 where all wind speed and directions values are zero is rubbish. There was a problem with the recorder, and those values should have been deleted. They will be very shortly. Thank you for letting me know. Best wishes, Elaine." (Elaine Fouhy, pers. comm.)